

**Fadiga de Materiais Estruturais:  
Fundamentos e Aplicações  
Crescimento de Trincas por  
Fadiga (Fatigue Crack Growth)**

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# AGENDA

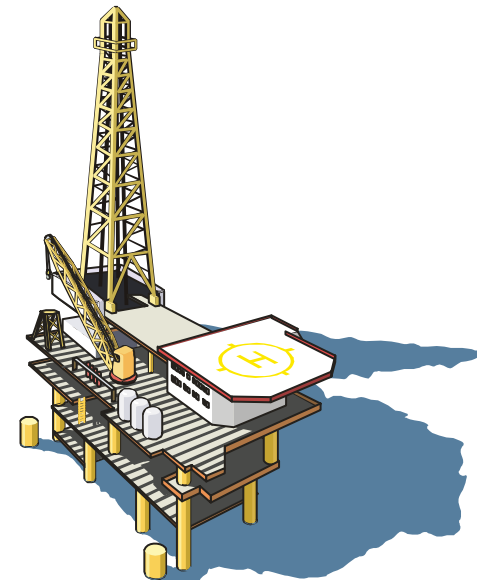
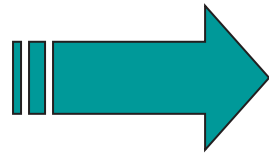
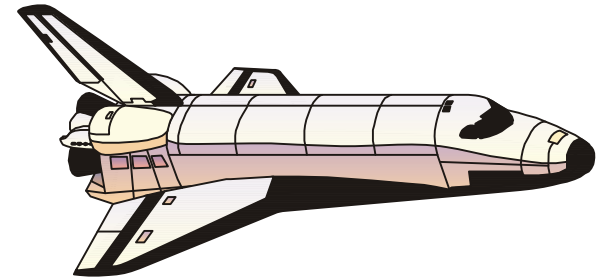
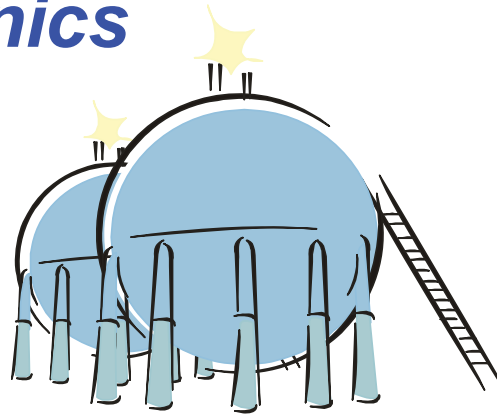
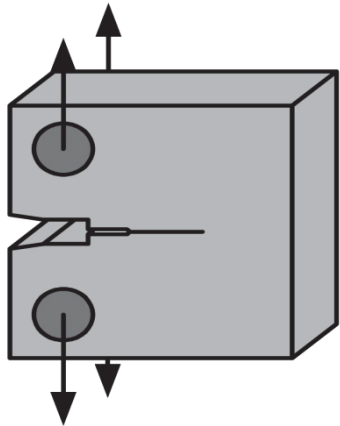
1. Introdução (*Introduction*)
2. Conceitos da MFEL (*LEFM Concepts*)
3. Curvas de  $da/dN$  -  $\Delta K$  (*da/dN Curves*)
4. Efeitos da Razão de Carga (*Effects of Load Ratio*)
5. Tendências nas Curvas  $da/dN$ - $\Delta K$  (*Trends in Fatigue Crack Growth*)
6. Estimativas da Vida à Fadiga (*Life Estimates*)
7. Limitações da MFEL (*Limitations of LEFM*)

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# Introduction

## ■ *Fracture Mechanics*

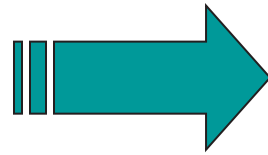
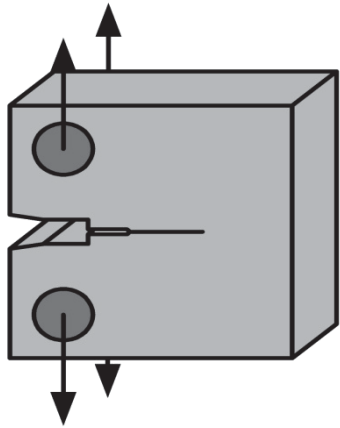


$K_I, J, CTOD$

**Notches = stress raisers**

# Introduction

- **Fracture Mechanics**



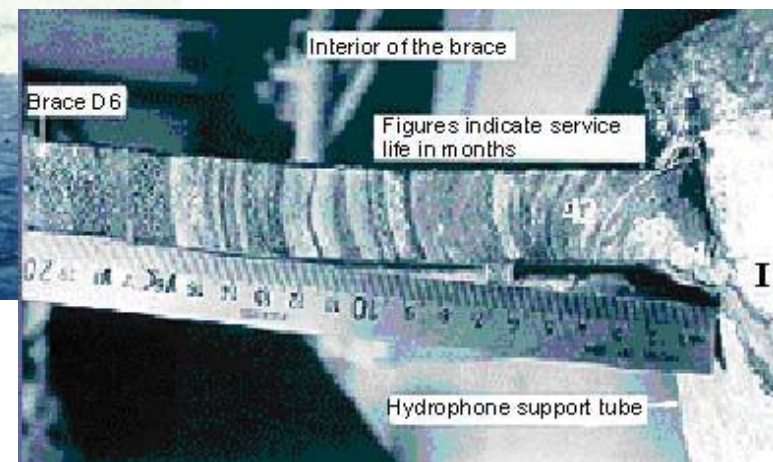
$K_I$ ,  $J$ , CTOD

# Falhas por Fadiga

Boeing 737 (Aloha Airlines - 1988)



# Falhas por Fadiga



- Plataforma *Alexander Kielland*

# AGENDA

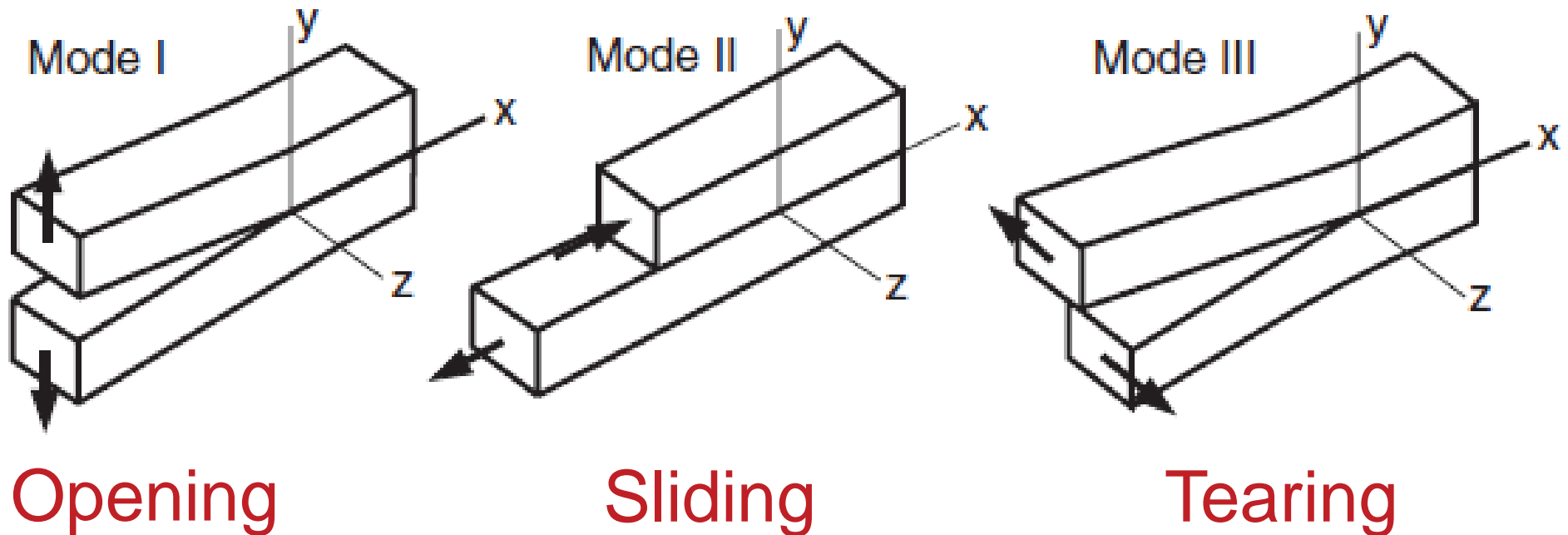
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# Mecânica da Fratura Elástica Linear

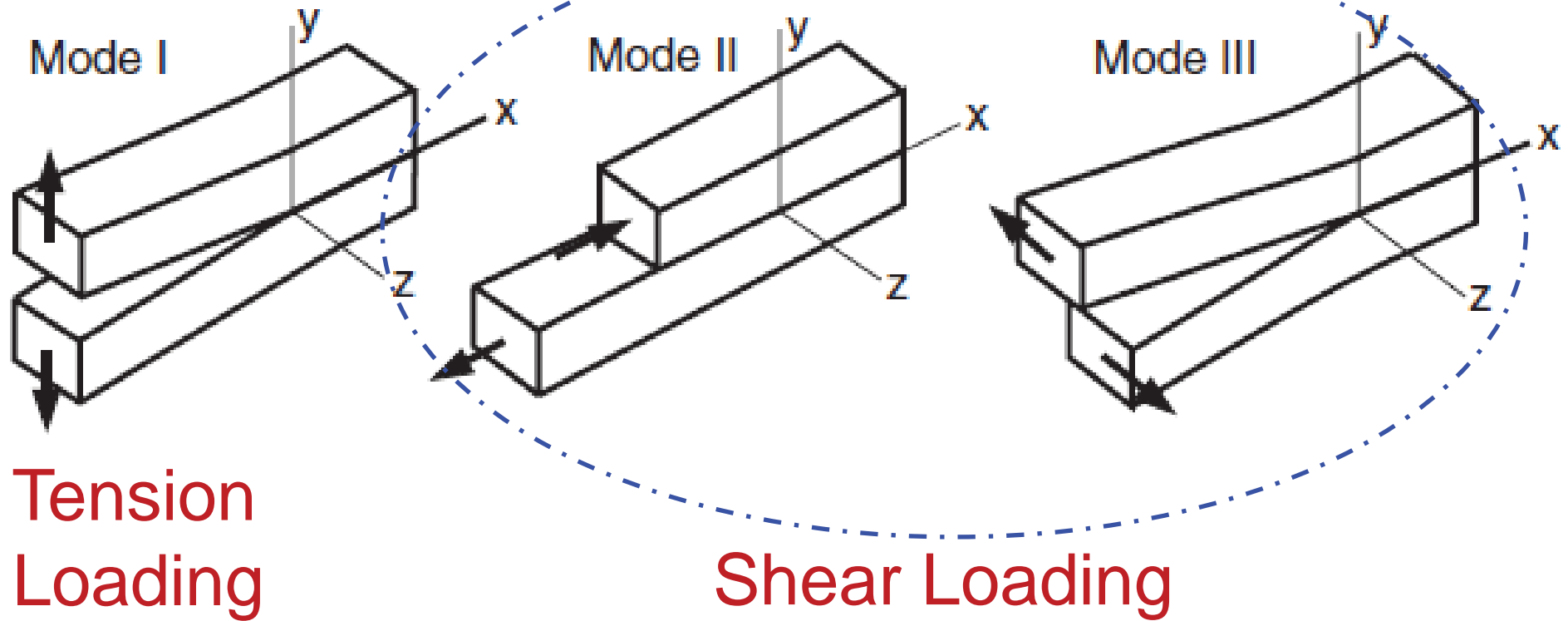
- Estudo **analítico** em sólidos na presença de **defeitos** que relaciona:
  - Carregamento Global.
  - Tamanho do Defeito.
  - Estado de Tensões/Deformações nas Vizinhanças do Defeito (trinca).
- Falhas (**dano**) estruturais **governada** pela **magnitude** e **distribuição** de tensões e deformações.

# Modos de Deformação



Mais favorável!

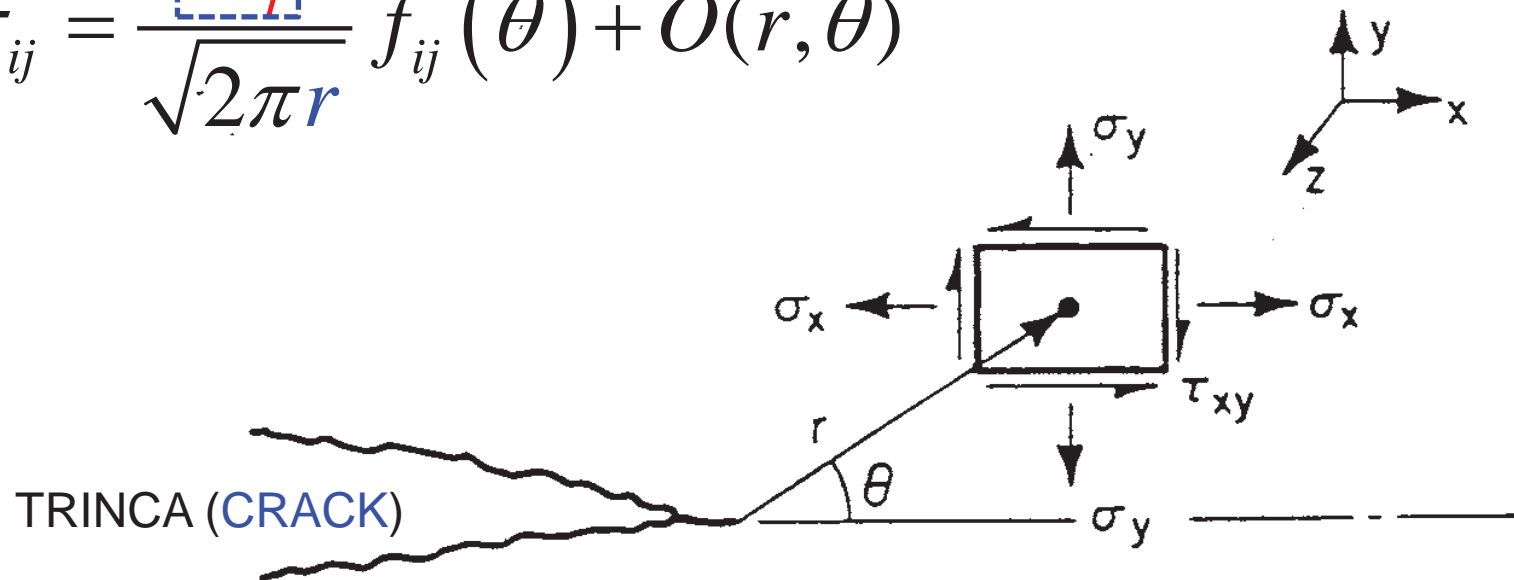
# Modos de Deformação



# Análise de Tensões para Trincas

- Fator de intensidade de tensões (Modo I)

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) + O(r, \theta)$$



Single-Parameter Description of Crack Tip Condition is the most Important Concepts in Fracture Mechanics

# Análise de Tensões para Trincas

- Campo de tensões elásticas (Modo I)

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[ 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right] + \dots$$

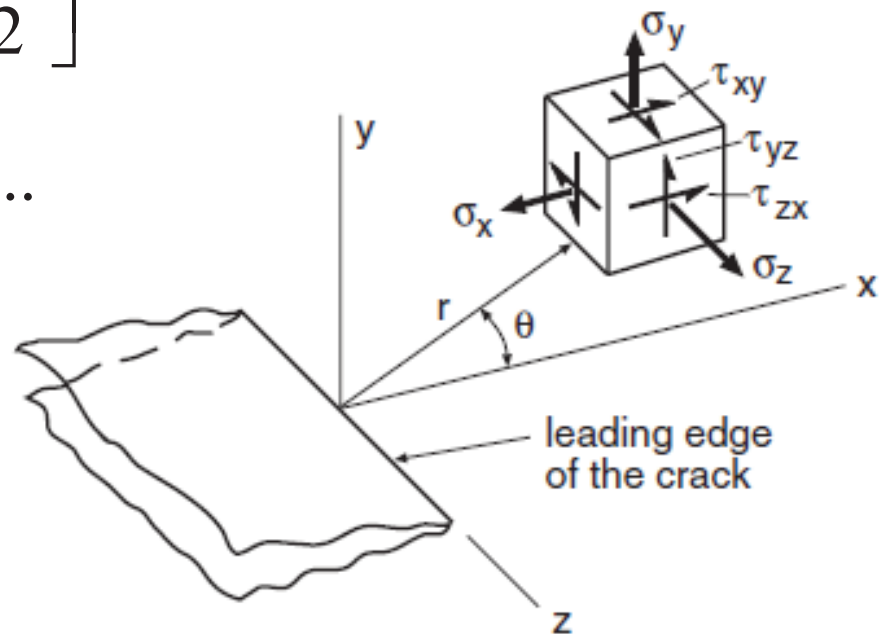
$$\tau_{zx} = \tau_{yz} = 0$$

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[ 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right] + \dots$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \sin \frac{\theta}{2} \cos \frac{3\theta}{2} + \dots$$

$$\sigma_{zz} = 0$$

$$\sigma_{zz} = \nu (\sigma_{xx} + \sigma_{yy})$$



# Análise de Tensões para Trincas

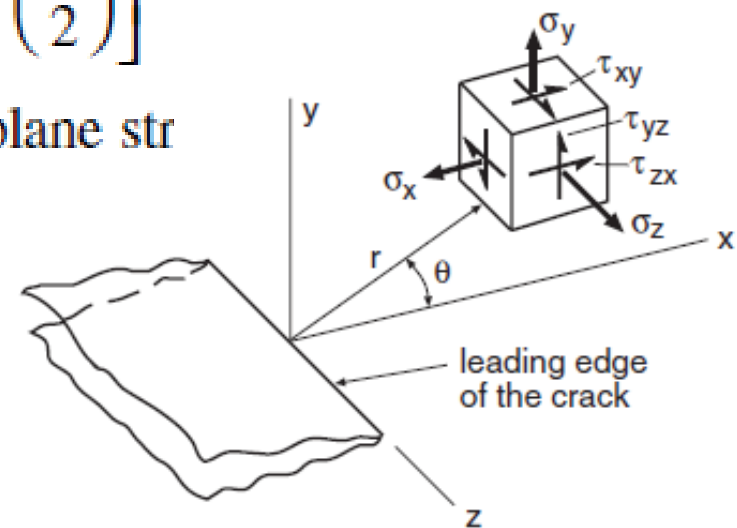
- Campo de deslocamentos (Modo I)

## Mode I

$$u_x = \frac{K_I}{2\mu} \sqrt{\frac{r}{2\pi}} \cos\left(\frac{\theta}{2}\right) \left[ \kappa - 1 + 2 \sin^2\left(\frac{\theta}{2}\right) \right]$$

$$u_y = \frac{K_I}{2\mu} \sqrt{\frac{r}{2\pi}} \sin\left(\frac{\theta}{2}\right) \left[ \kappa + 1 - 2 \cos^2\left(\frac{\theta}{2}\right) \right]$$

*Note:*  $\mu$  is the shear modulus.  $\kappa = 3 - 4\nu$  (plane str



# Análise de Tensões para Trincas

- Campo de tensões elásticas (Modo I)

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[ 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right]$$

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[ 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right]$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \sin \frac{\theta}{2} \cos \frac{3\theta}{2}$$

$$\sigma_{zz} = 0$$

$$\sigma_{zz} = \nu (\sigma_{xx} + \sigma_{yy})$$

$$\theta=0$$

$$\sigma_{xx} = \sigma_{yy} \frac{K_I}{\sqrt{2\pi r}}$$

$$\tau_{xy} = 0$$

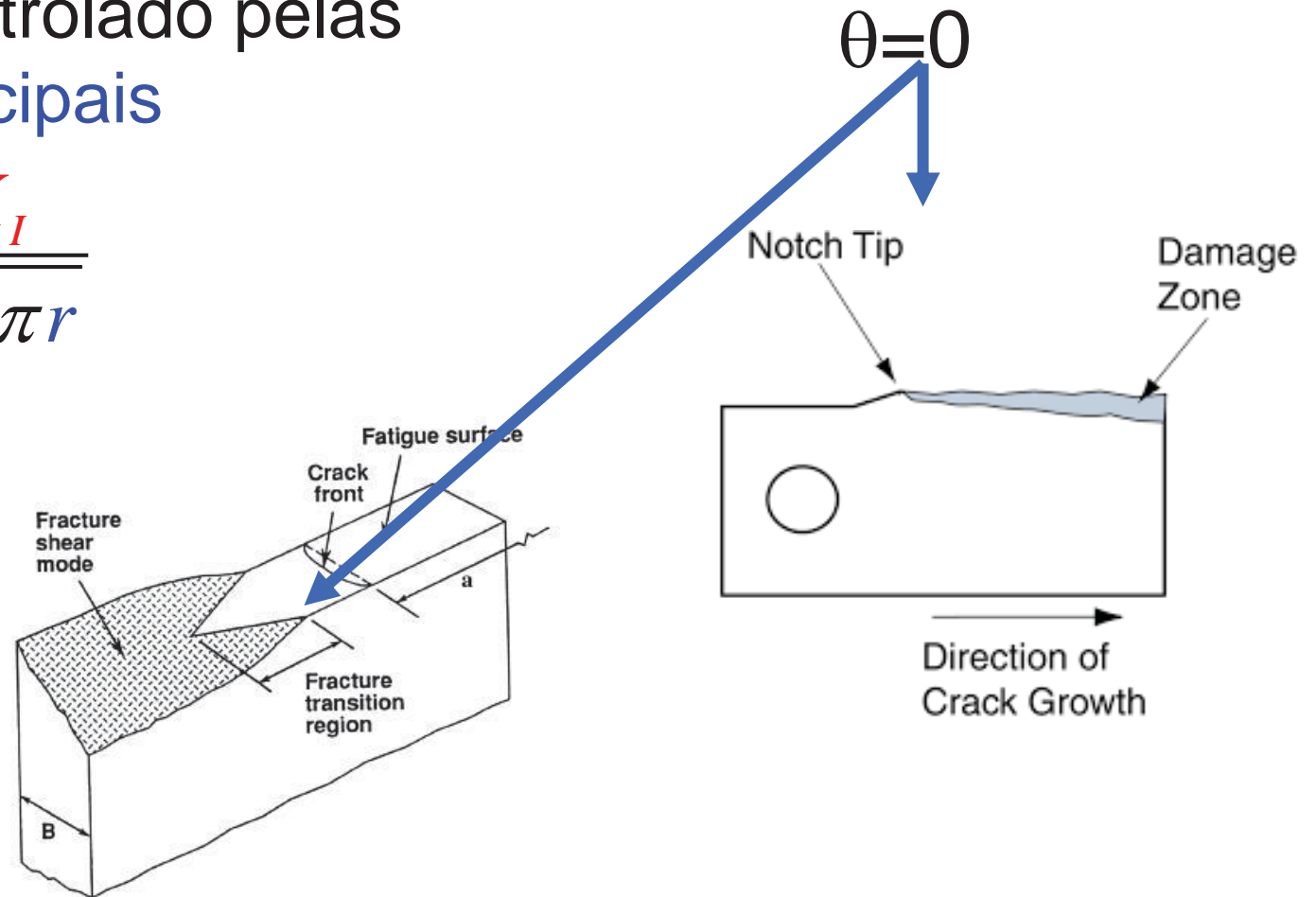
Plano da Trinca = Plano Principal

# Análise de Tensões para Trincas

O dano é controlado pelas  
Tensões Principais

$$\sigma_{xx} = \sigma_{yy} \frac{K_I}{\sqrt{2\pi r}}$$

$$\tau_{xy} = 0$$

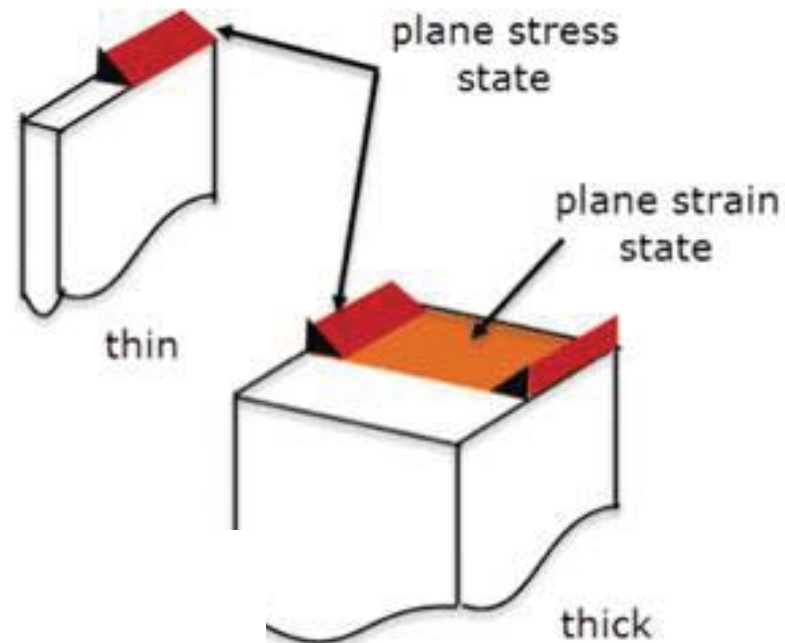
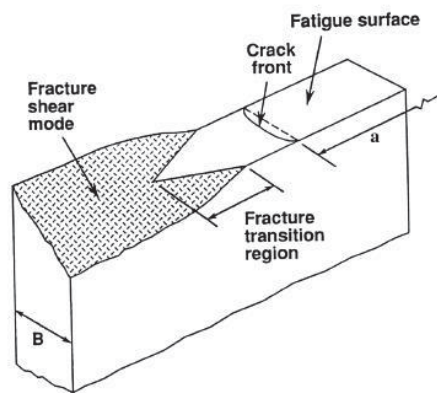
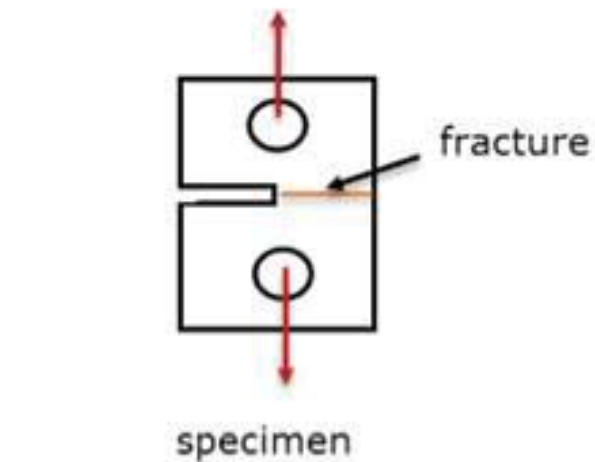




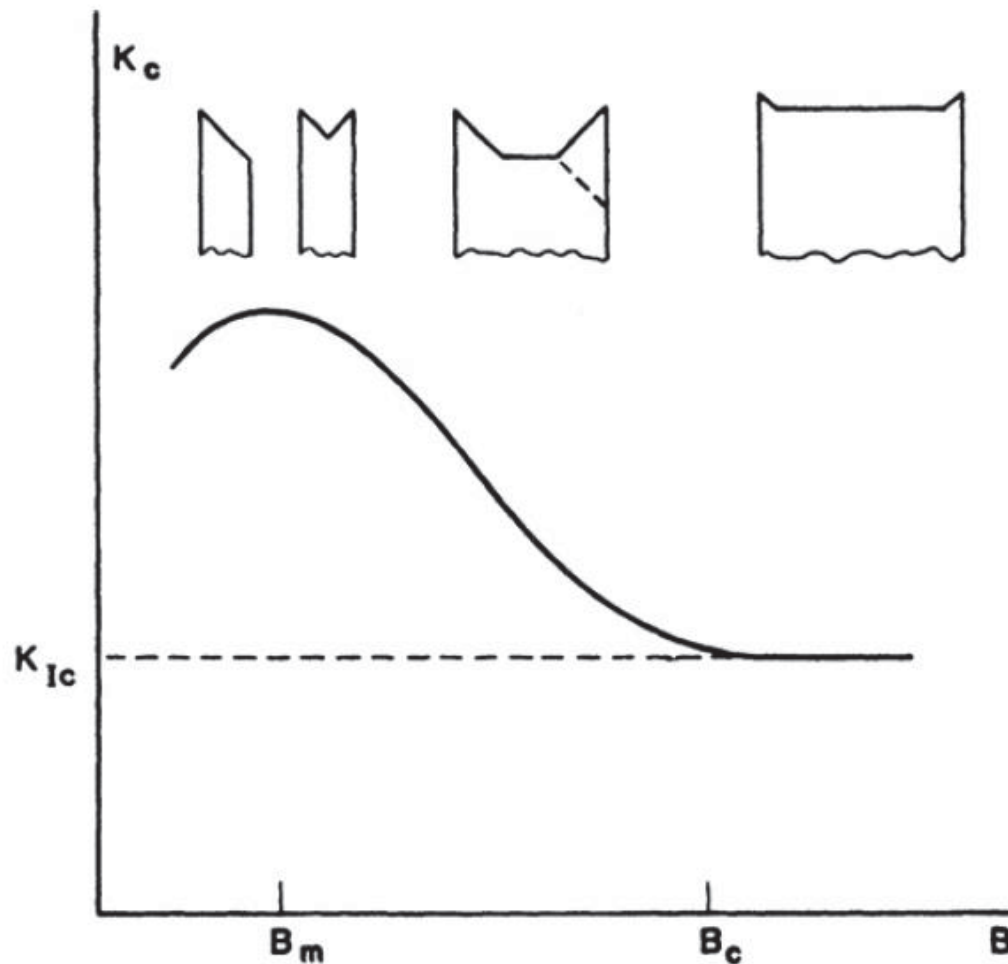
# Análise de Tensões para Trincas

O dano é controlado pelas  
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$$\sigma_{xx} = \sigma_{yy} \frac{K_I}{\sqrt{2\pi r}}$$



# Slant Fracture vs. Flat Fracture

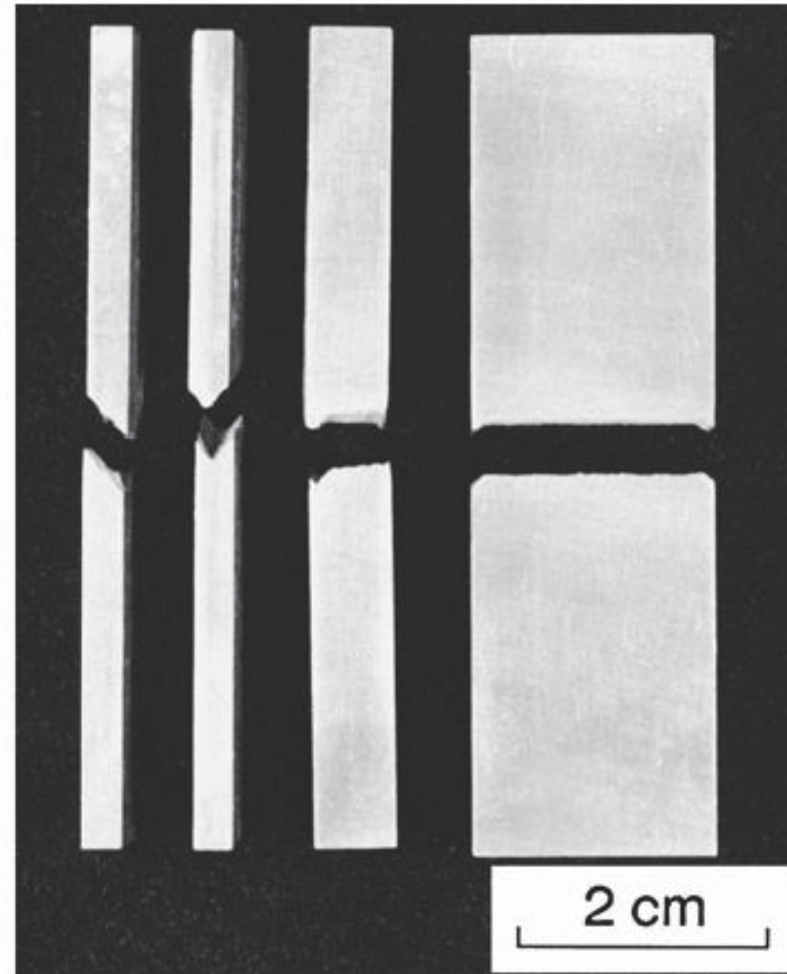
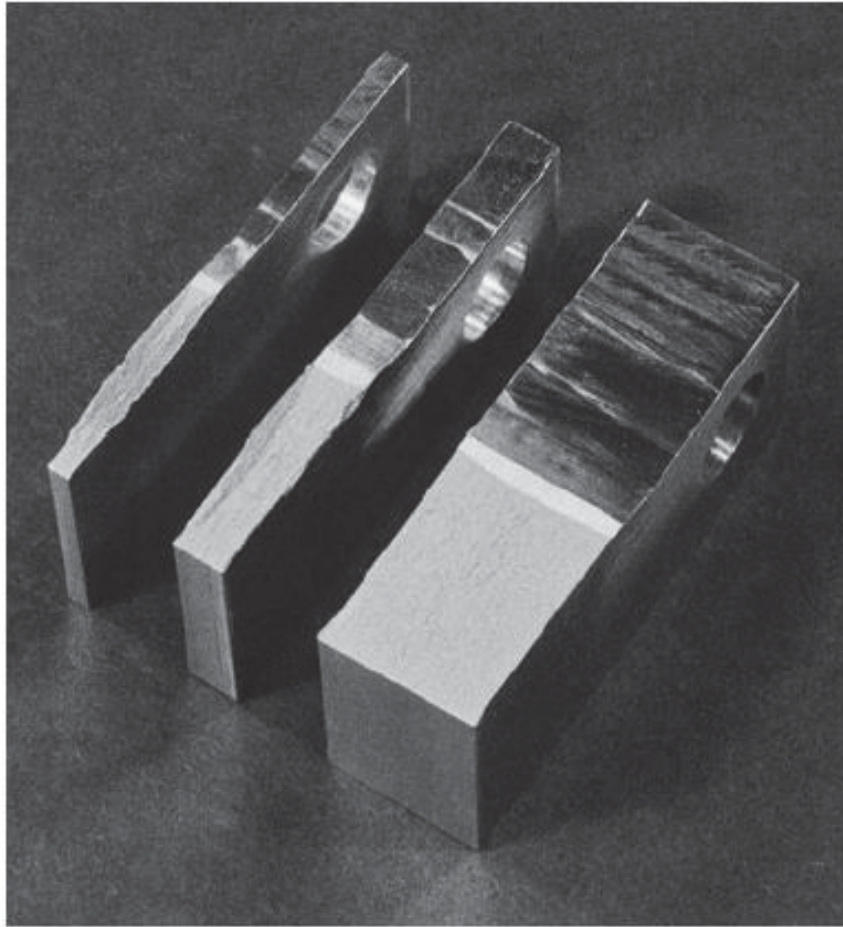


$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta)$$

$K_{Ic}$  is a measure of a given material to resist fracture in presence of a crack

Figure 3.17 Critical Mode I stress intensity factor as a function of specimen thickness.

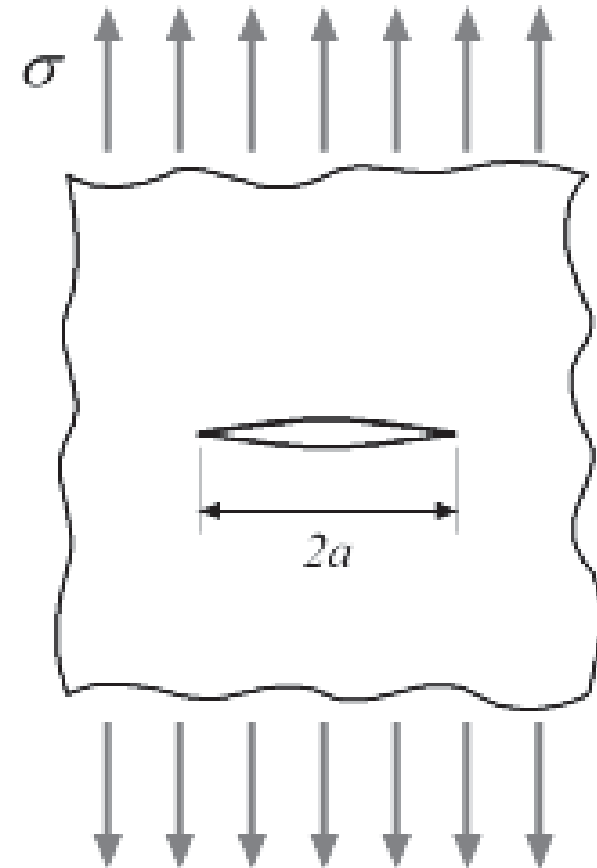
# Slant Fracture vs. Flat Fracture



# K para Componentes/CPs

- Placa Plana

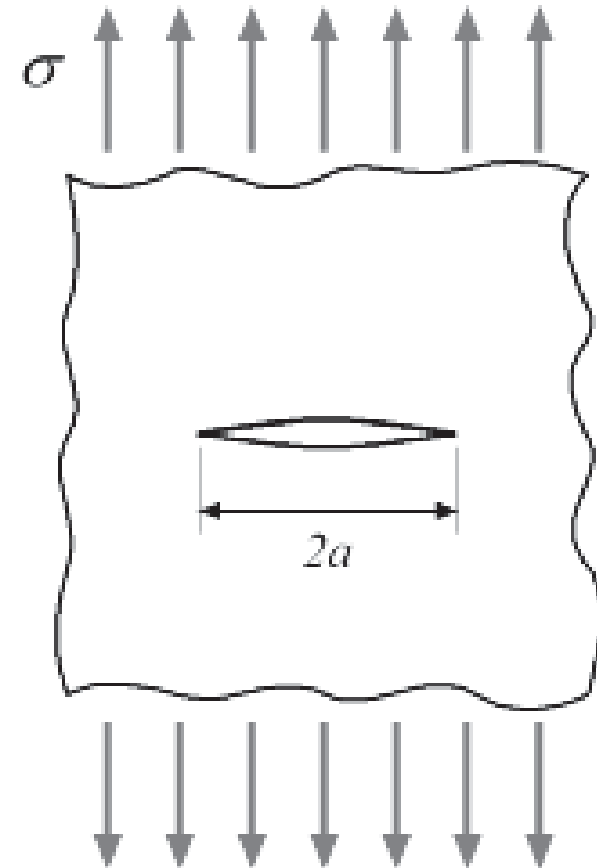
$$K_I = \sigma \sqrt{\pi a}$$



# K para Componentes/CPs

- Placa Plana

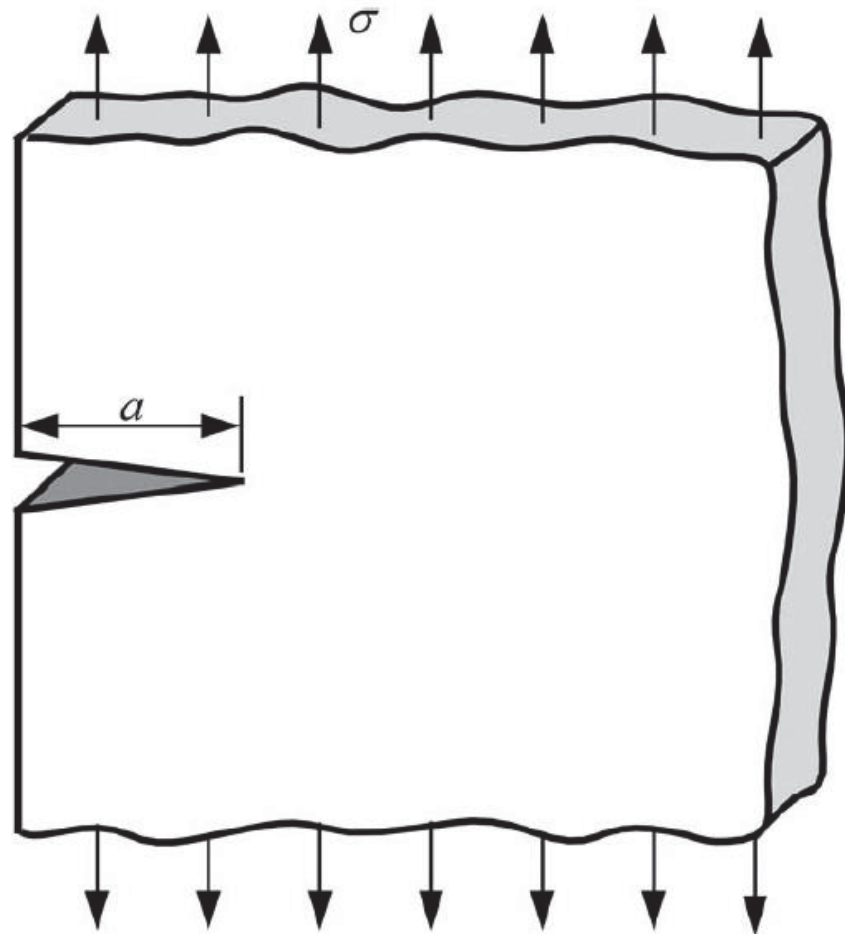
$$K_I = \sigma \sqrt{\pi a}$$



# K para Componentes/CPs

- Placa Plana

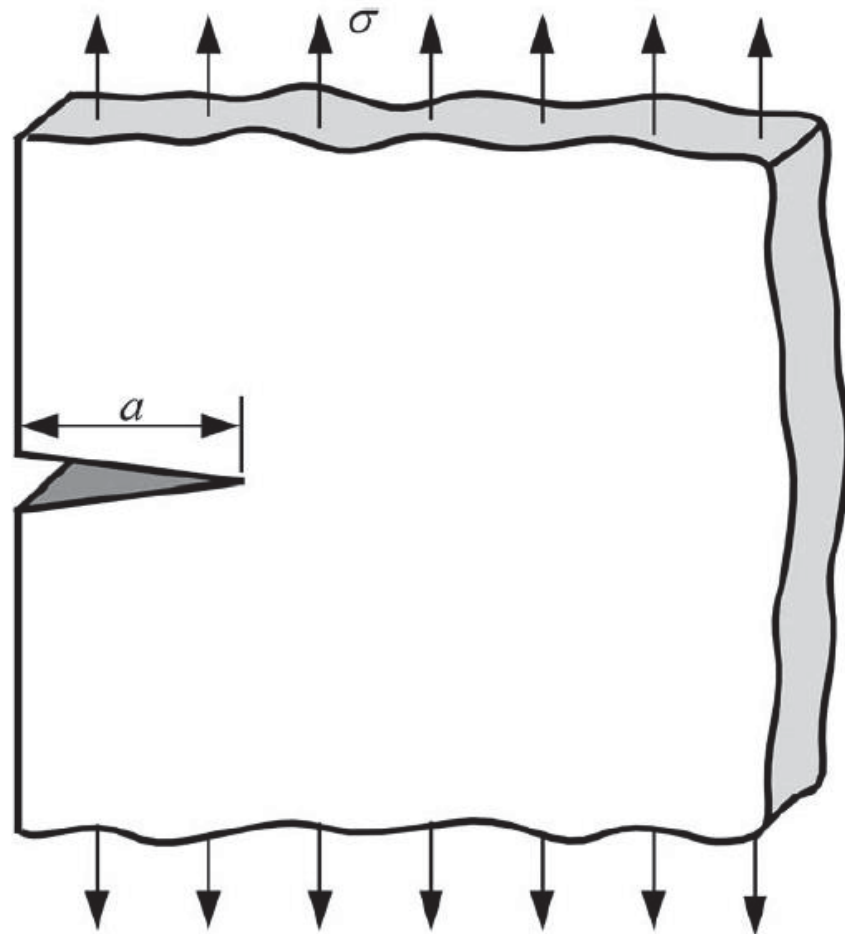
$$K_I = 1.12\sigma\sqrt{\pi a}$$



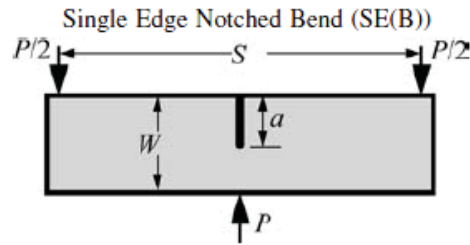
# K para Componentes/CPs

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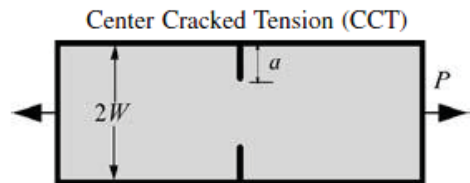
$$K_I = 1.12\sigma\sqrt{\pi a}$$



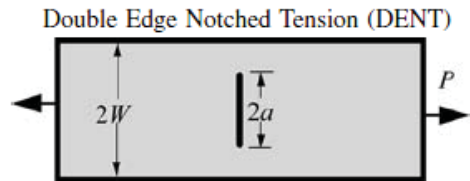
# K para Componentes/CPs



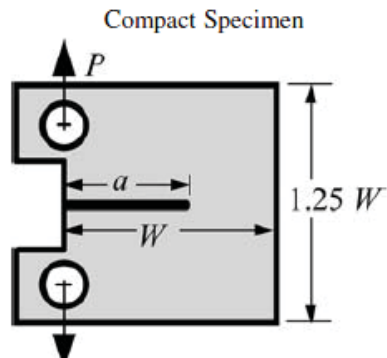
$$\frac{3 \frac{S}{W} \sqrt{\frac{a}{W}}}{2 \left(1 + 2 \frac{a}{W}\right) \left(1 - \frac{a}{W}\right)^{3/2}} \left[ 1.99 - \frac{a}{W} \right. \\ \left. \left(1 - \frac{a}{W}\right) \left\{ 2.15 - 3.93 \left(\frac{a}{W}\right) + 2.7 \left(\frac{a}{W}\right)^2 \right\} \right]$$



$$\sqrt{\frac{\pi a}{4W}} \sec\left(\frac{\pi a}{2W}\right) \left[ 1 - 0.025 \left(\frac{a}{W}\right)^2 \right. \\ \left. + 0.06 \left(\frac{a}{W}\right)^4 \right]$$



$$\sqrt{\frac{\pi a}{2W}} \left[ 1.122 - 0.561 \left(\frac{a}{W}\right) - 0.205 \left(\frac{a}{W}\right)^2 \right. \\ \left. + 0.471 \left(\frac{a}{W}\right)^3 + 0.190 \left(\frac{a}{W}\right)^4 \right]$$

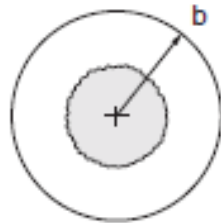
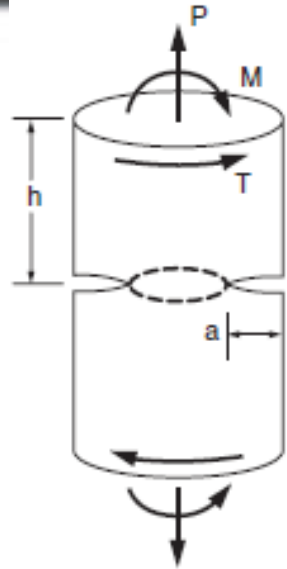


$$\frac{2 + \frac{a}{W}}{\left(1 - \frac{a}{W}\right)^{3/2}} \left[ 0.886 + 4.64 \left(\frac{a}{W}\right) - 13.32 \left(\frac{a}{W}\right)^2 \right. \\ \left. + 14.72 \left(\frac{a}{W}\right)^3 - 5.60 \left(\frac{a}{W}\right)^4 \right]$$

$$K_I = \frac{P}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$



# K para Componentes/CPs



$$K = FS_g \sqrt{\pi a}$$

$$\alpha = a/b$$

$$\beta = 1 - \alpha$$

$$K_I = FS_g \sqrt{\pi a}$$

(a) Axial load  $P$ :  $S_g = \frac{P}{\pi b^2}$ ,  $F = 1.12$  (10%,  $a/b \leq 0.21$ )

$$F = \frac{1}{2\beta^{1.5}} \left[ 1 + \frac{1}{2}\beta + \frac{3}{8}\beta^2 - 0.363\beta^3 + 0.731\beta^4 \right]$$

(b) Bending moment  $M$ :  $S_g = \frac{4M}{\pi b^3}$ ,  $F = 1.12$  (10%,  $a/b \leq 0.12$ )

$$F = \frac{3}{8\beta^{2.5}} \left[ 1 + \frac{1}{2}\beta + \frac{3}{8}\beta^2 + \frac{5}{16}\beta^3 + \frac{35}{128}\beta^4 + 0.537\beta^5 \right]$$

(c) Torsion  $T$ ,  $K = K_{III}$ :  $S_g = \frac{2T}{\pi b^3}$ ,  $F = 1.00$  (10%,  $a/b \leq 0.09$ )

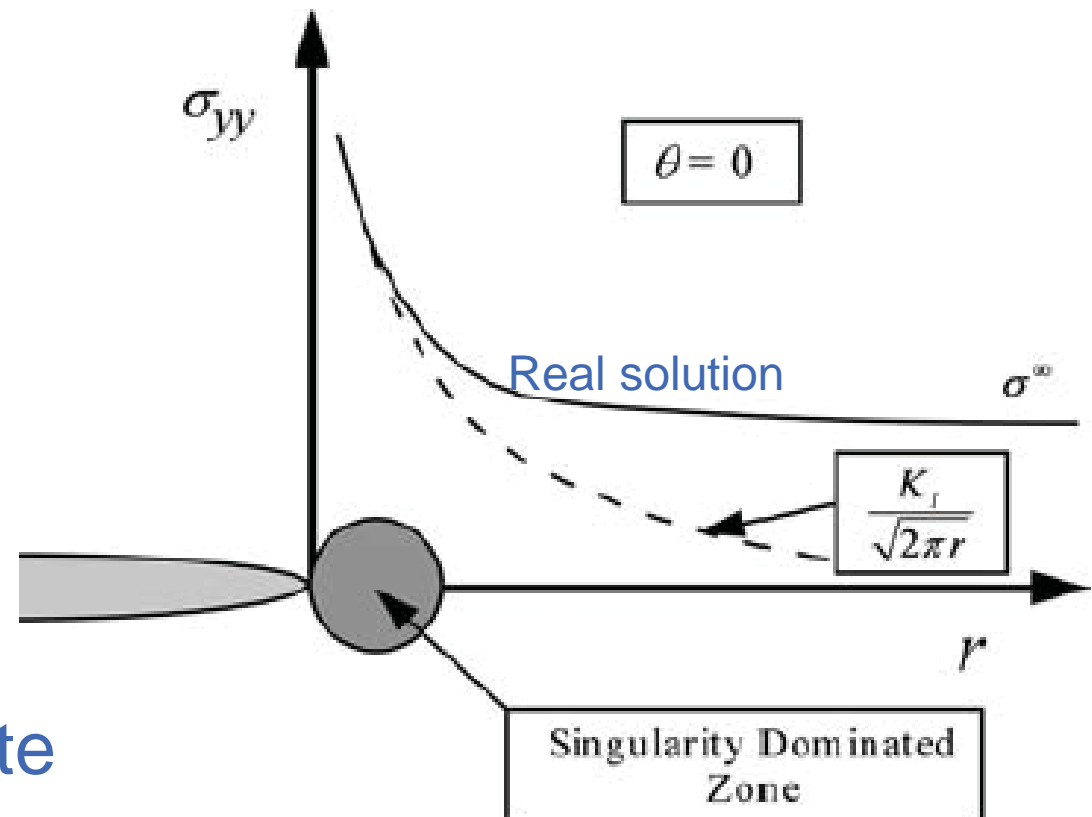
$$F = \frac{3}{8\beta^{2.5}} \left[ 1 + \frac{1}{2}\beta + \frac{3}{8}\beta^2 + \frac{5}{16}\beta^3 + \frac{35}{128}\beta^4 + 0.208\beta^5 \right]$$

# Dominância K

- Campo de tensões  $\theta=0$  (Modo I)

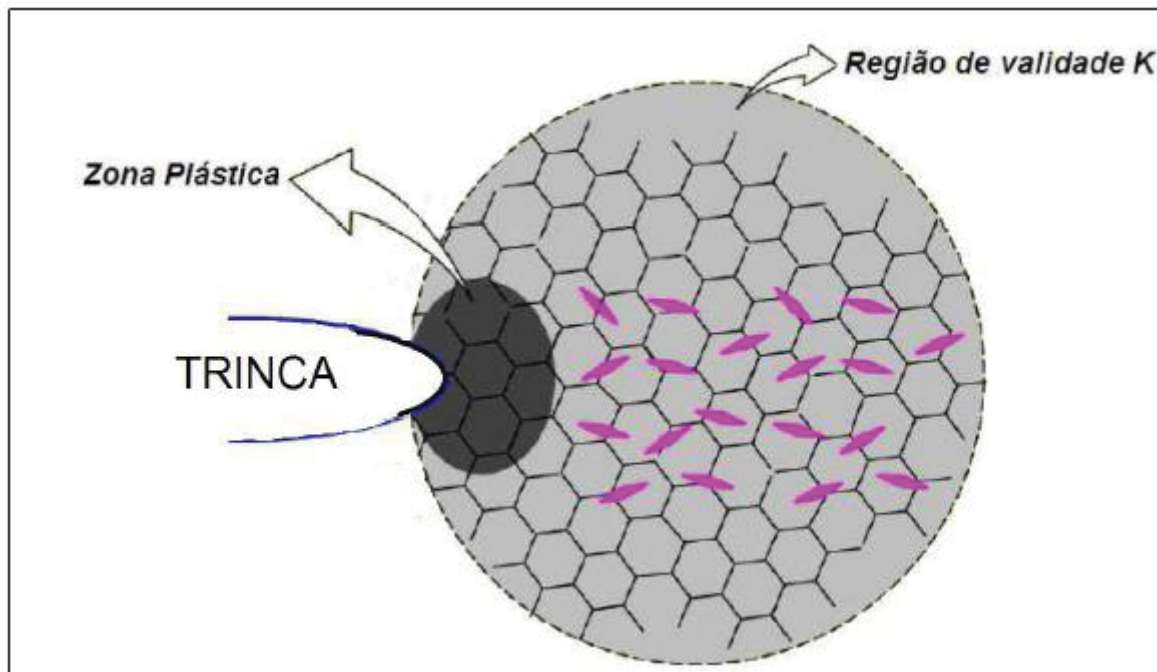
$$\sigma_{xx} = \sigma_{yy} \frac{K_I}{\sqrt{2\pi r}}$$

- **Close** to crack tip the singularity **dominates** the stress field.
- **Far** from crack tip the stress fields are **governed** by the **remote** boundary conditions.



# Dominância K

**Região de Dominância K:** A região R onde o campos de tensões/deformações são descritos pela solução elástica.



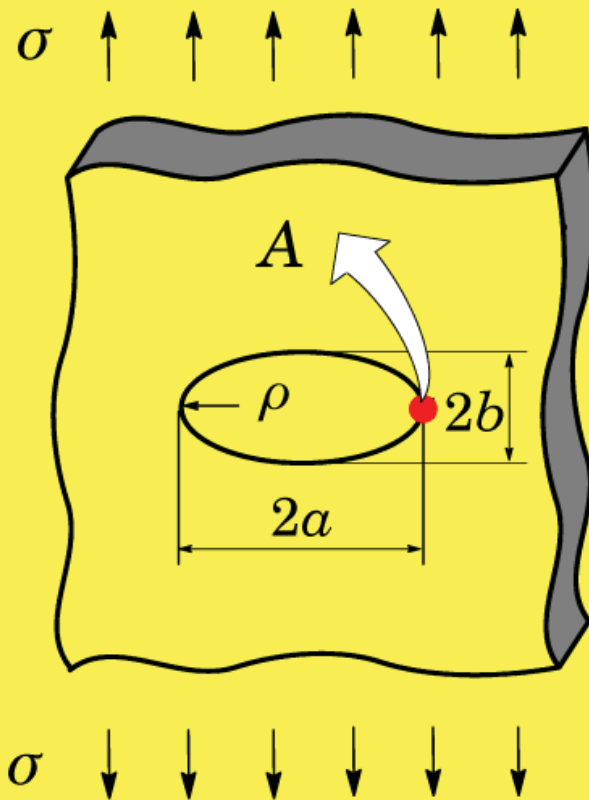
$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta)$$

K define a amplitude da singularidade

$$\sigma_{ij} \approx K$$

K defines **completely** the crack tip conditions

# $K_I$ vs. $K_t$



Concentração de Tensões:

$$K_T = \frac{\sigma_A}{\sigma} = 1 + \frac{2a}{b}$$

$a \gg b$ :

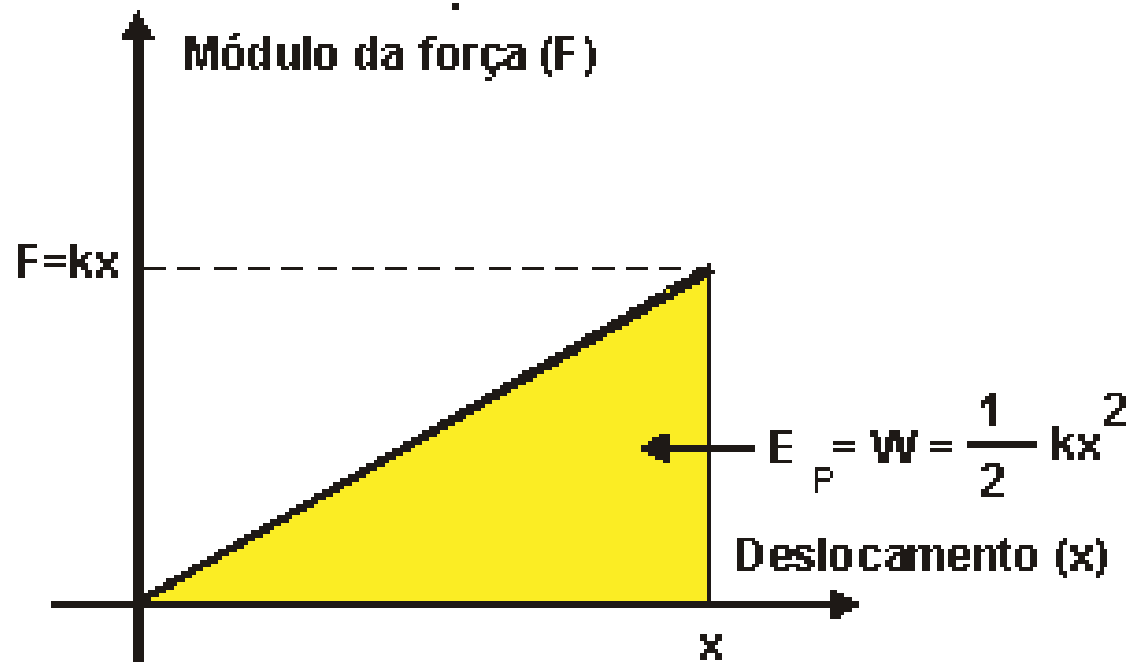
$$\rho = \frac{b^2}{a} \rightarrow K_T \approx 2 \sqrt{\frac{a}{\rho}}$$

Trincas:

$$\rho \rightarrow 0 \rightarrow K_T \rightarrow \infty$$

# Strain Energy

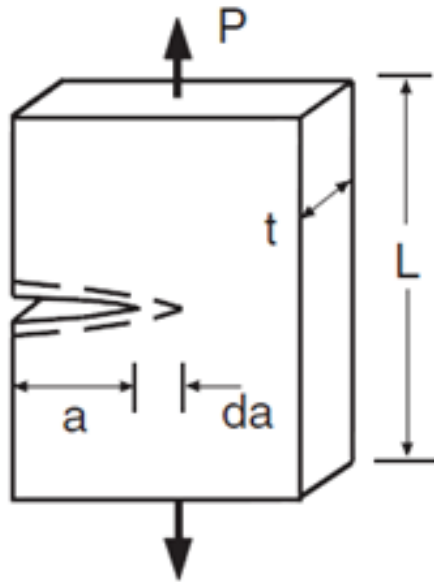
## Mola Elástica



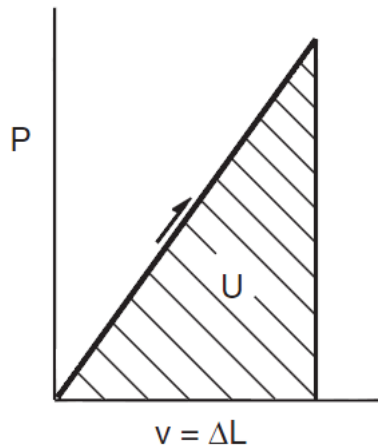
$$U = \frac{1}{2} kx^2$$



# Strain Energy Release Rate (G)



- Cracked body
- Material behavior: Linear-elastic
- Similar to linear **spring**:
  - Potential energy **U** stored as result of elastic strains through its volume
  - $U = Pv/2$  (triangular **área** under P-v curve)

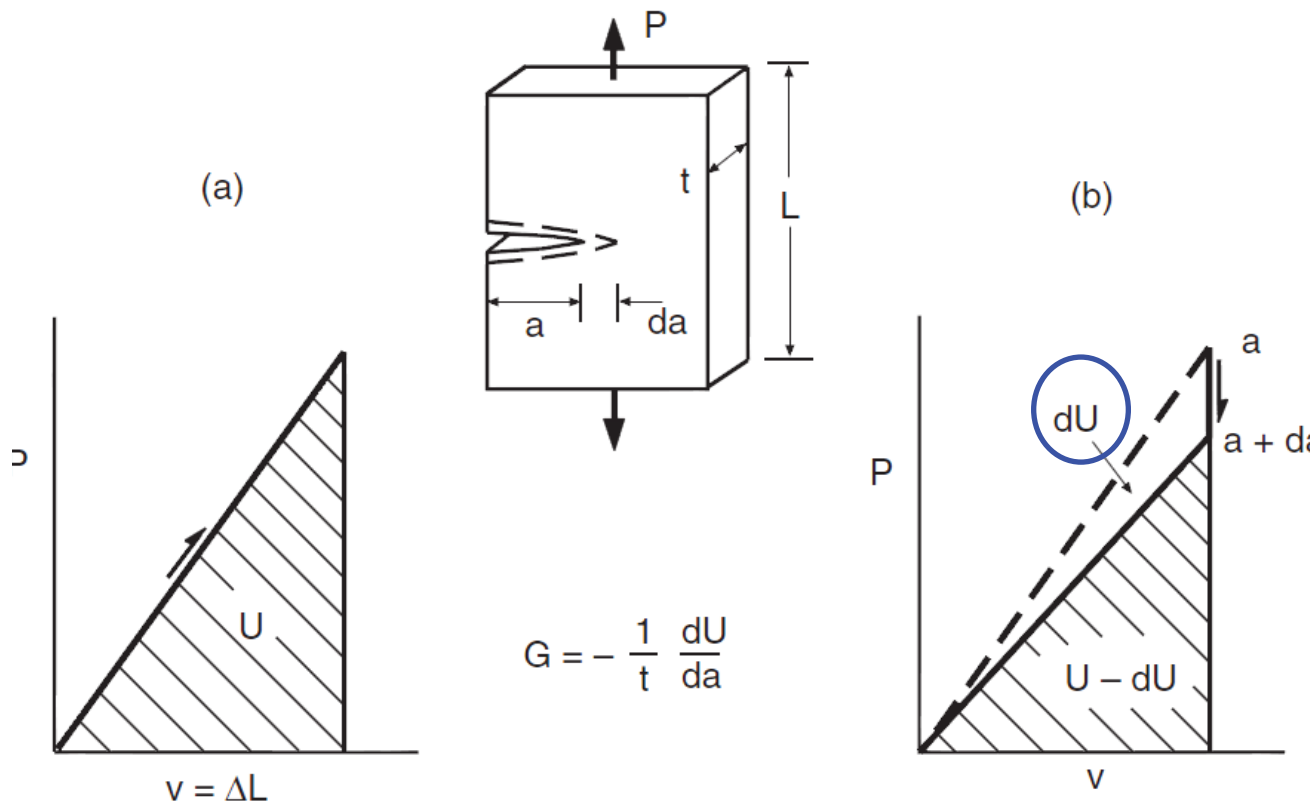


$$U = \frac{1}{2} P v$$

# Strain Energy Release Rate (G)

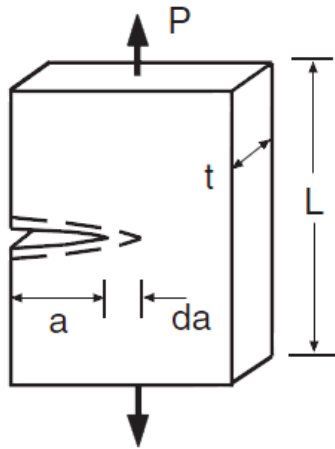
If crack growths  $da$   $\rightarrow$  Stiffness decrease  $\rightarrow$   $U \downarrow$   
 $\downarrow$   
 Release of energy

Rate of change of potential energy with increase in crack area is defined as  $\underline{G}$



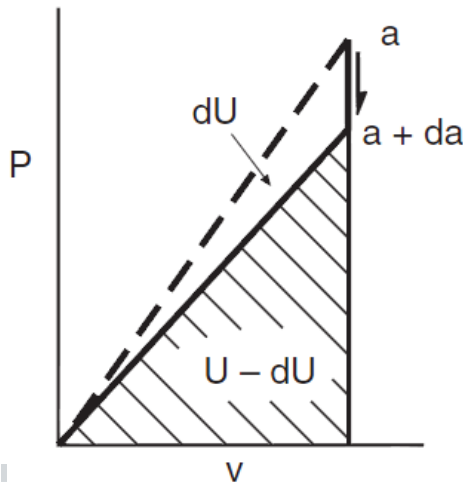
$$G = -\frac{1}{t} \frac{dU}{da}$$

# Strain Energy Release Rate (G)



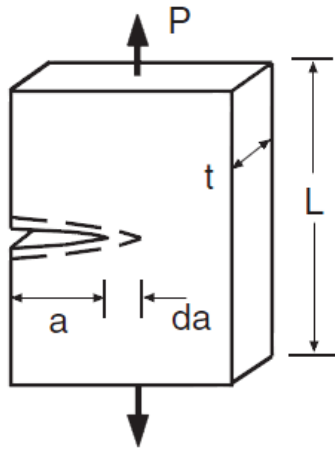
$$G = -\frac{1}{t} \frac{dU}{da}$$

- Change in crack area =  $t da$
- Negative sign produces positive  $G$  value
- $G$  characterizes the energy per unit crack area required to extend the crack
- $G$  is a fundamental physical quantity controlling the behavior of the crack



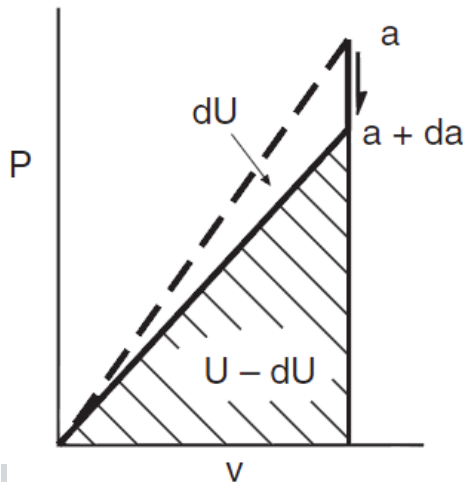


# Strain Energy Release Rate (G)

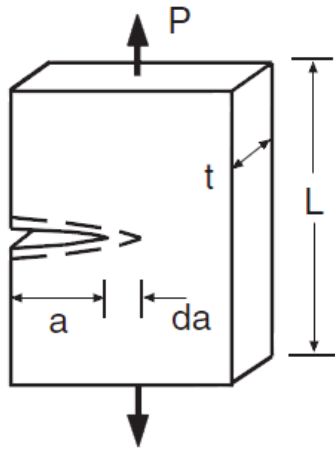


$$G = -\frac{1}{t} \frac{dU}{da}$$

- For **brittle** material all released energy is used to create new surface on the crack surface
- For **ductile** material almost all released energy is used to deform plastically the material at the crack tip.

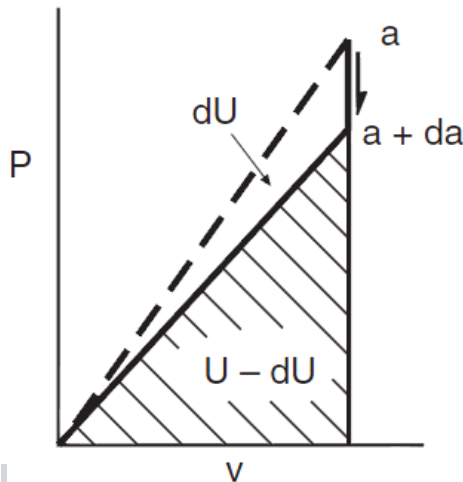


# Taxa de Liberação de Energia (G)



$$G = -\frac{1}{t} \frac{dU}{da}$$

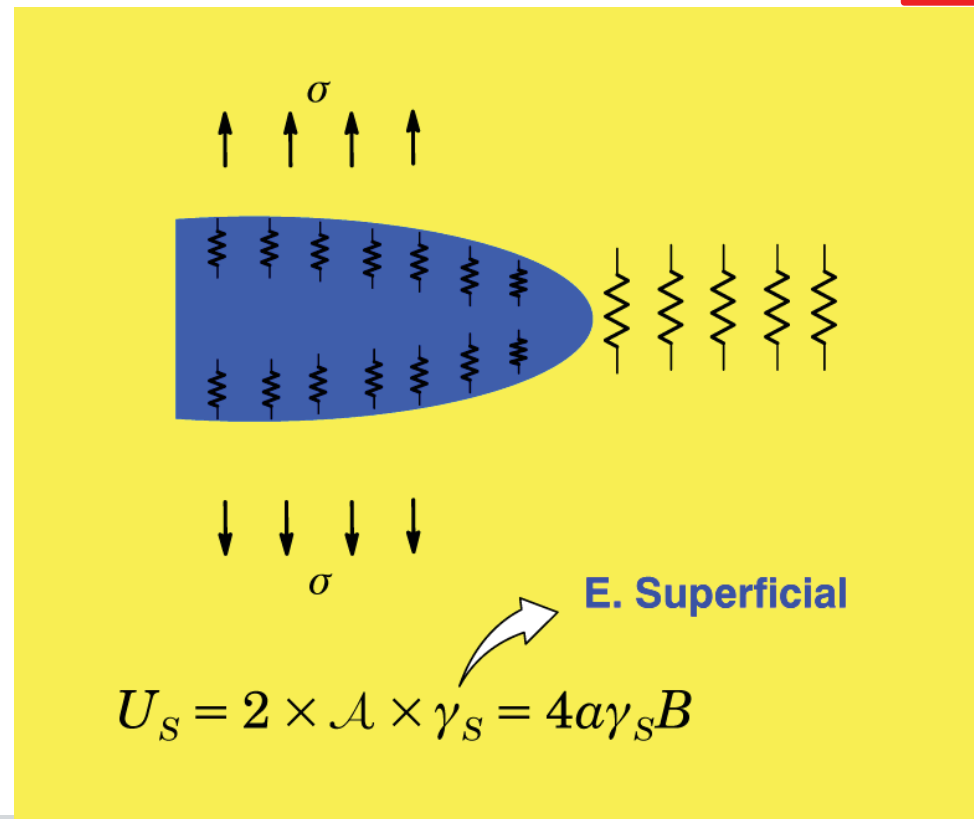
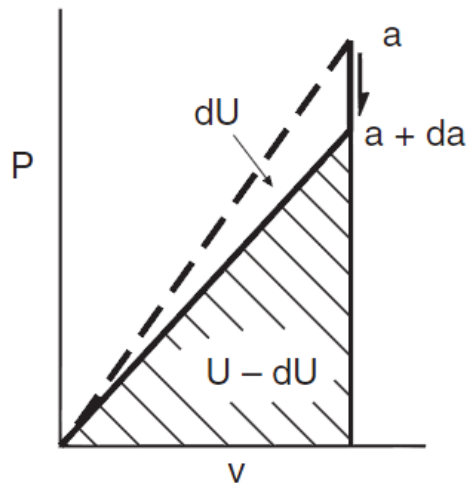
- Irwin (1956)
- G : medida da energia **disponível** para um incremento no tamanho da trinca.
- Devem ser **“vencidas”** dois tipos de resistência para a trinca incrementar seu comprimento
  1. Prover energia suficiente para criar **novas superfícies**;
  2. Prover energia para deformar **plasticamente** o material na ponta da trinca.



# Taxa de Liberação de Energia (G)

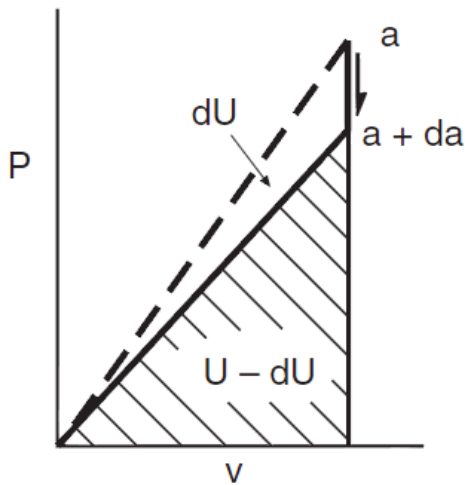
- Energia superficial

$$G = -\frac{1}{t} \frac{dU}{da}$$



# Taxa de Liberação de Energia (G)

Energia Superficial  
+  
Dissipação Plástica



$$G = - \frac{1}{t} \frac{dU}{da}$$

$$\sigma_f = \sqrt{\frac{2(\gamma_s + \gamma_p)E}{\pi a}}$$

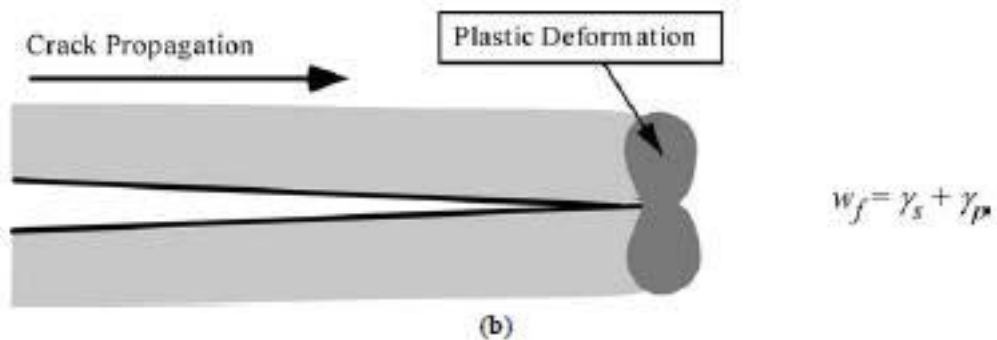
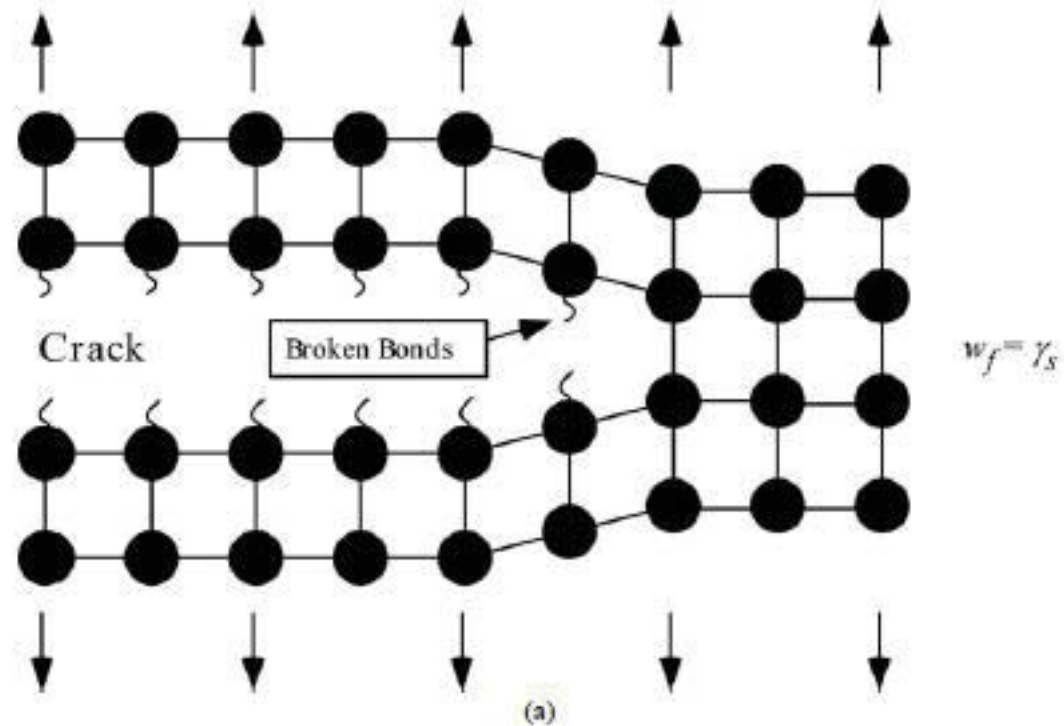
$$U_s^* = 4a(\gamma_s + \gamma_p)B$$

$\gamma_s \ll \gamma_p$

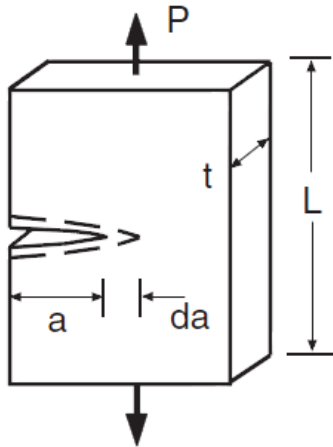
E. de Dissipação Plástica

Não é Constante!

# Energia Superficial + Dissipação Plástica



# Energia Superficial + Dissipação Plástica



- **Trabalho** necessário a ser feito pelas forças externas para **Fraturar** ( incremento  $\Delta a$  do tamanho da trinca) o corpo trincado:

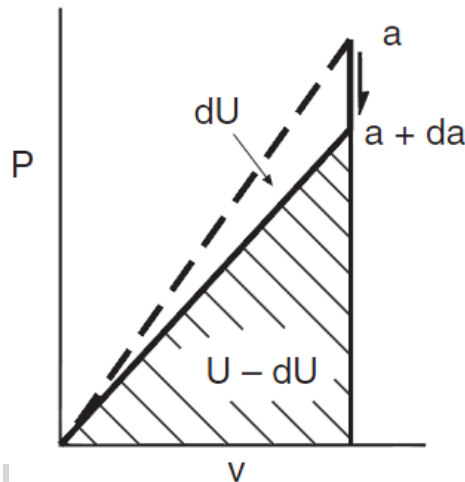
$$W_{fratura} = f(\gamma_s, \gamma_p)$$

$$W_{fratura} = U_s^* = 4a(\gamma_s + \gamma_p)B$$

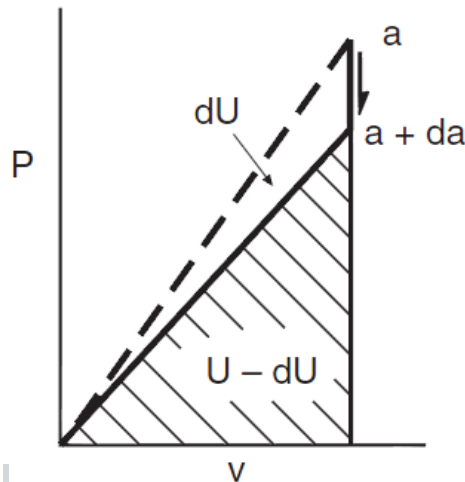
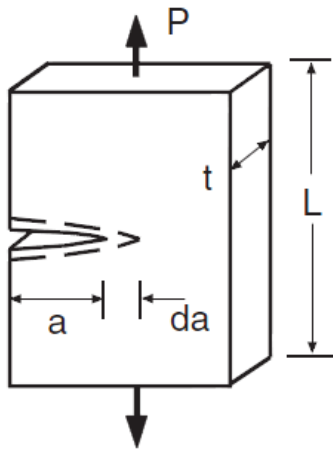
$$\gamma_s \ll \gamma_p$$

$\gamma_p$  : E. Dissipação Plástica

$\gamma_s$  : E. Superficial



# Energia Superficial + Dissipação Plástica



- Energia Disponível vs. Energia Requerida

$$G = -\frac{1}{t} \frac{dU_p}{da}$$

vs.

$$G_c = \frac{dU_s^*}{dA}$$

Força Motriz

Tenacidade

# Design based on LEFM

$$K_c = S_c \sqrt{\pi a_c} f\left(\frac{a_c}{w}\right)$$

Loading,  $S$



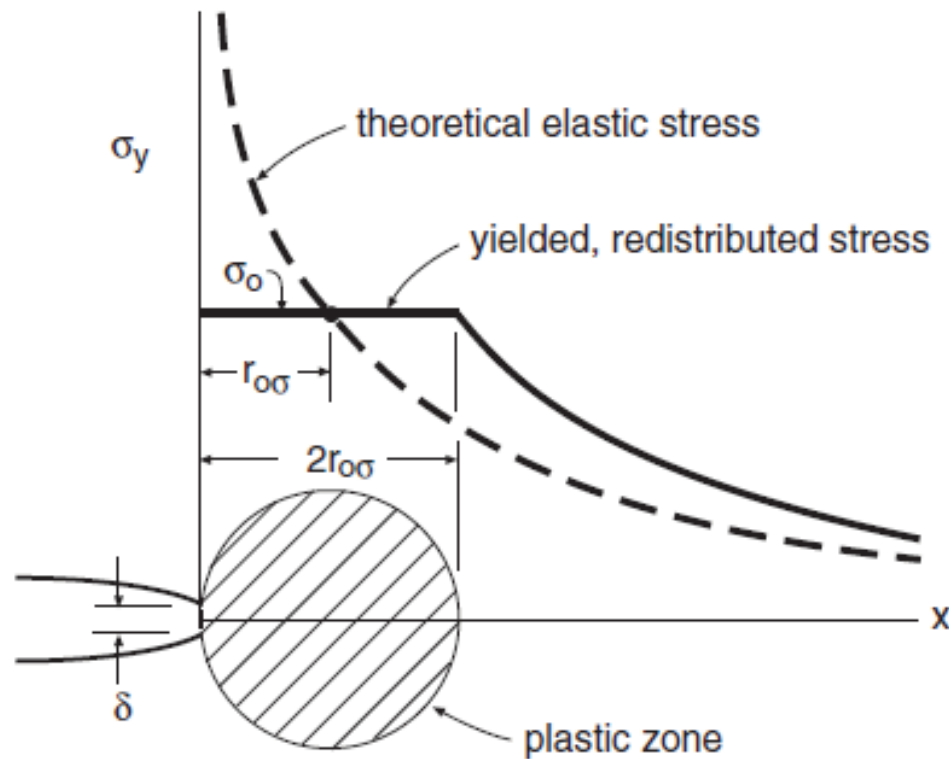
Crack Size,  $a$

Material,  $K_c$



# Plastic Zone Size

Monotonic



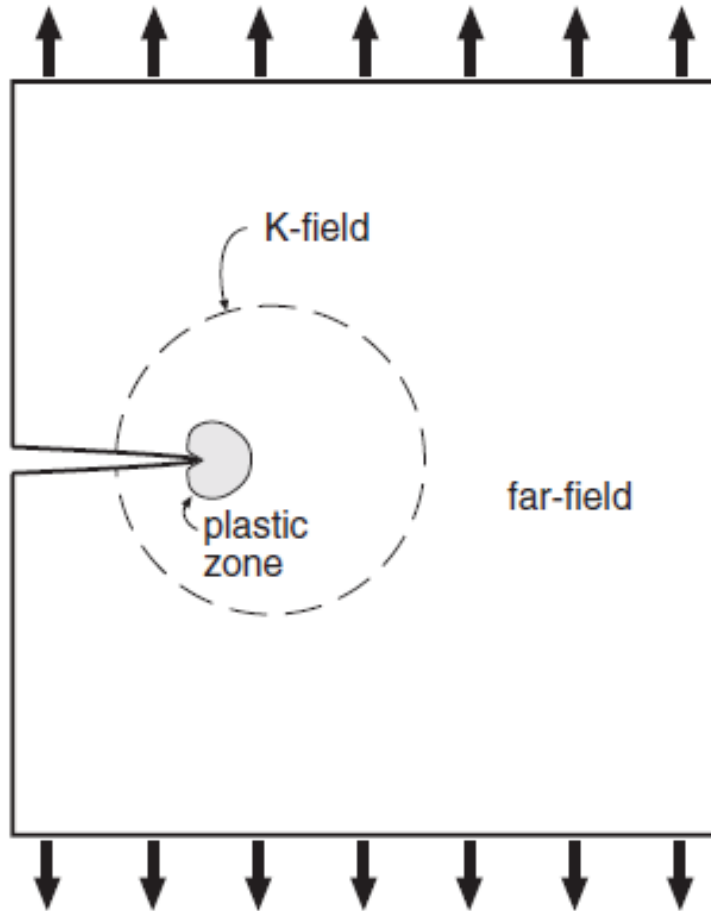
Plane Stress

$$2r_{0\sigma} = \frac{1}{\pi} \left( \frac{K}{\sigma_0} \right)^2$$

Plane Strain

$$2r_{0\varepsilon} = \frac{1}{3\pi} \left( \frac{K}{\sigma_0} \right)^2$$

# Validity of LEFM

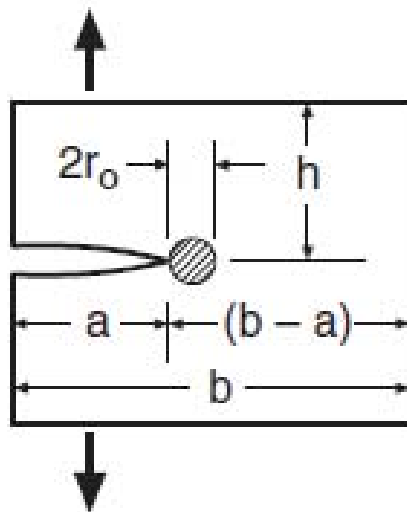


K-fields **surrounds** and **control** the behavior of plastic zone near crack tip area

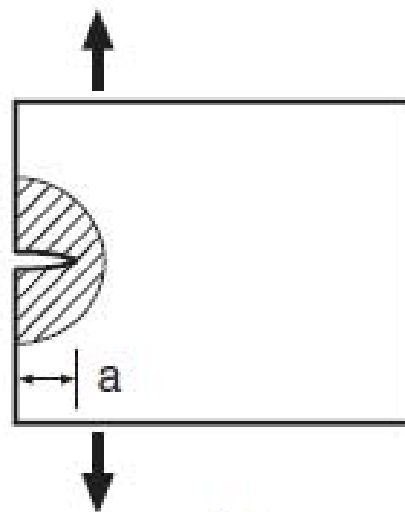
Plastic zone can be treated as a **black box**

K characterizes the **severity** of crack despite the presence of limited plasticity

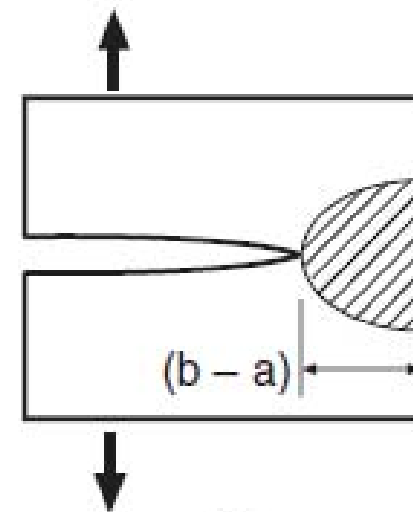
# Validity of LEFM



(a)

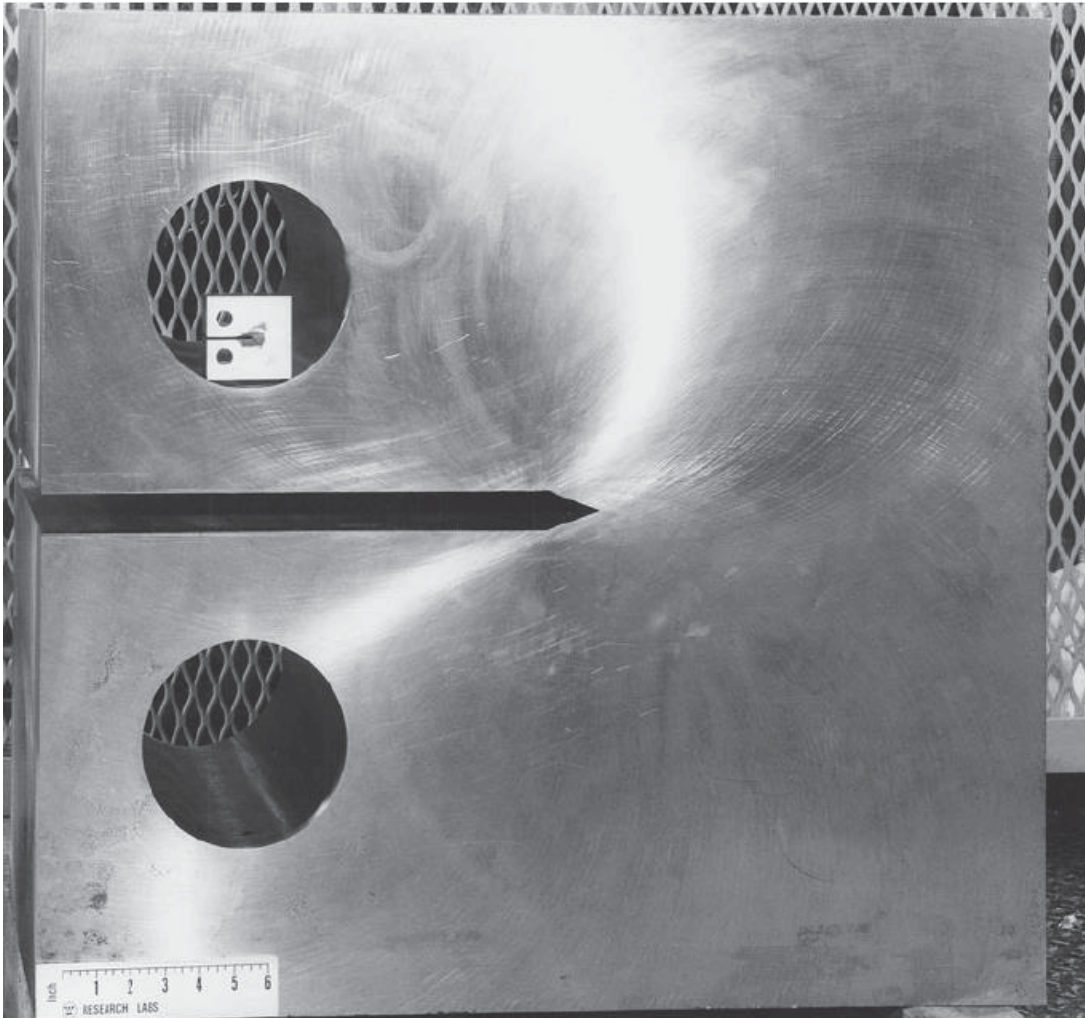


(b)



(c)

# Validity of LEFM



Small plastic zone

$$a, (b - a), h \geq \frac{4}{\pi} \left( \frac{K}{\sigma_o} \right)^2$$

Plane strain

$$t, a, (b - a), h \geq 2.5 \left( \frac{K}{\sigma_o} \right)^2$$

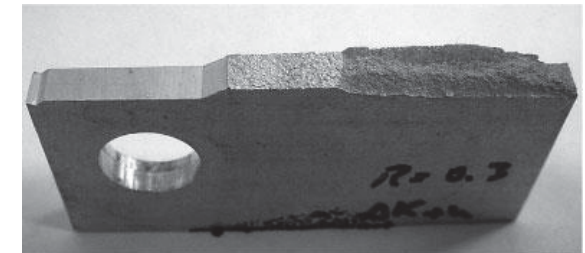
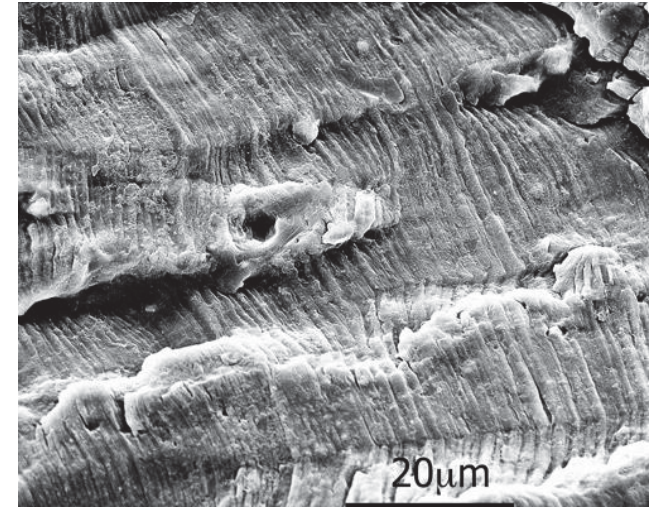
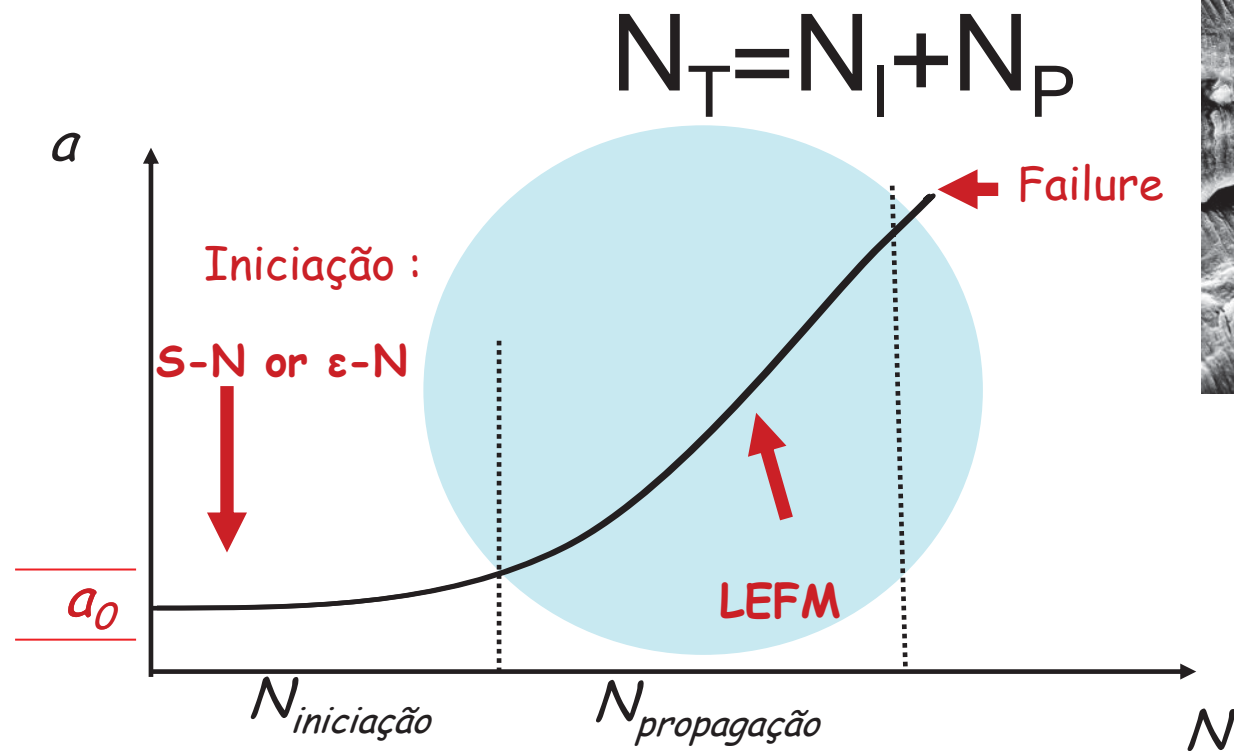
24X plastic size

# AGENDA

1. *Introdução (Introduction)*
2. *Conceitos da MFEL (LEFM Concepts)*
3. **Curvas de  $da/dN$  -  $\Delta K$  ( $da/dN$  Curves)**
4. *Efeitos da Razão de Carga (Effects of Load Ratio)*
5. *Tendências nas Curvas  $da/dN$ - $\Delta K$  (Trends in Fatigue Crack Growth)*
6. *Estimativas da Vida à Fadiga (Life Estimates)*
7. *Limitações da MFEL (Limitations of LEFM)*

# Avaliação da Vida à Fadiga

Vida à fadiga de um componente:

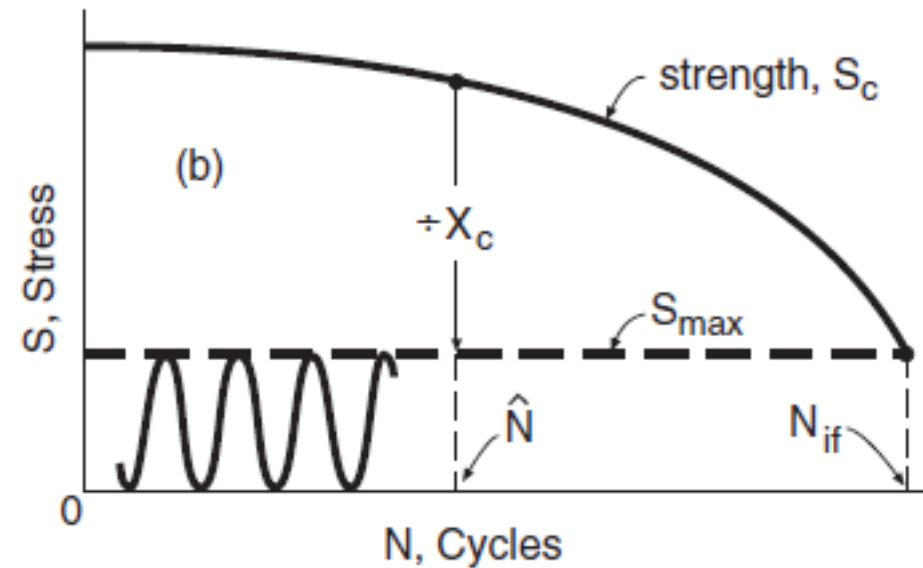
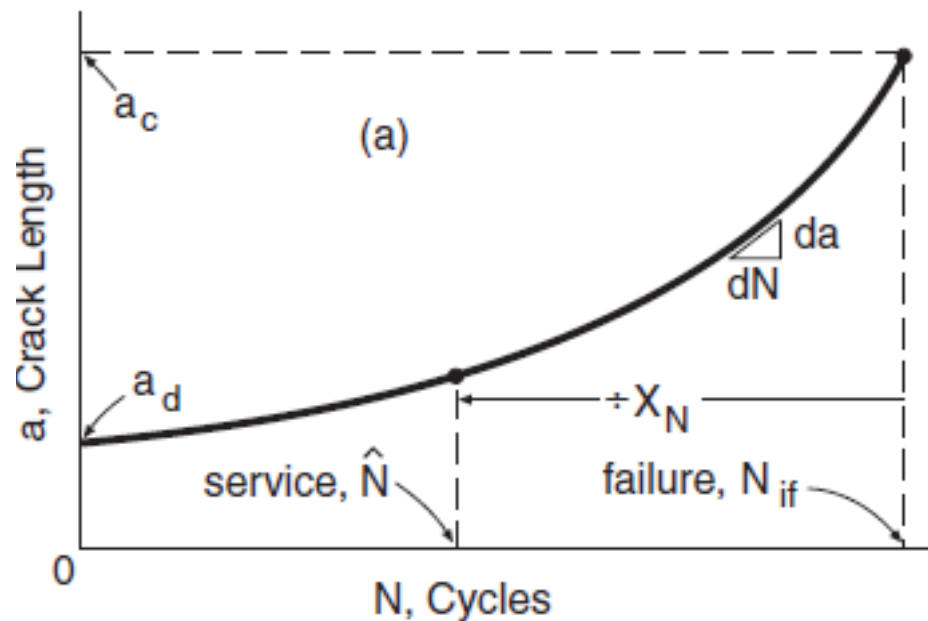


(a)

# Fatigue Crack Growth

## Crack Growth with Cyclic Loading

$$S_c = \frac{K_c}{F \sqrt{\pi a}}$$

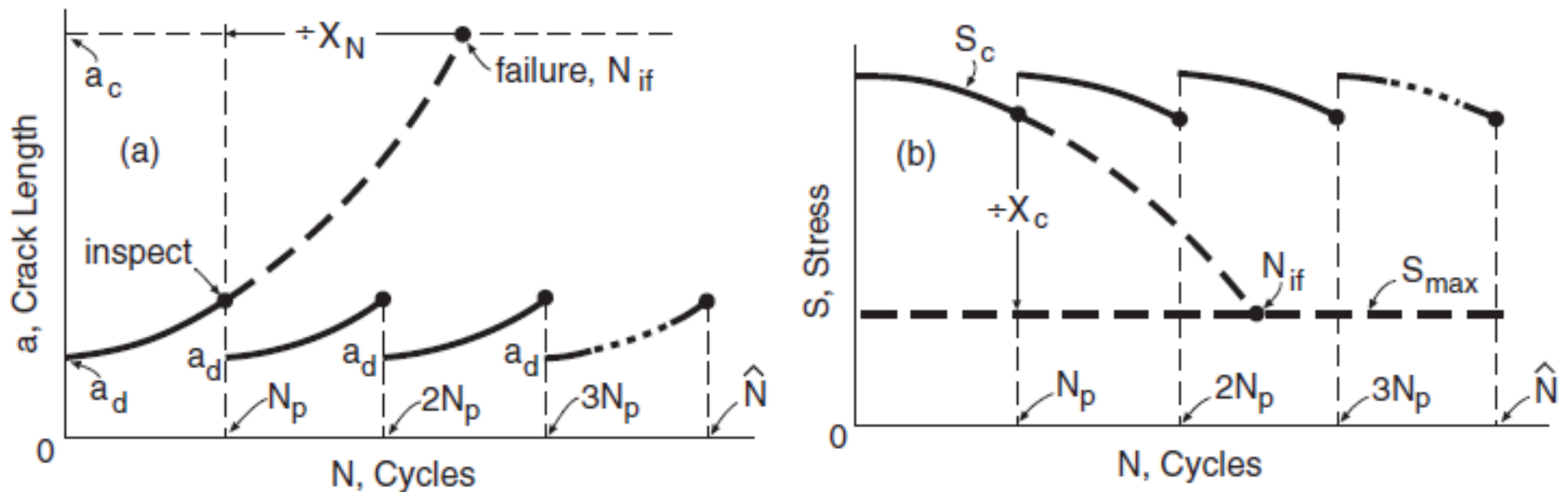


$$X_N = \frac{N_{if}}{\hat{N}}$$

$$X_c = \frac{S_c}{S_{max}} \quad \text{Brittle Fracture}$$

# Need for Crack Growth Analysis

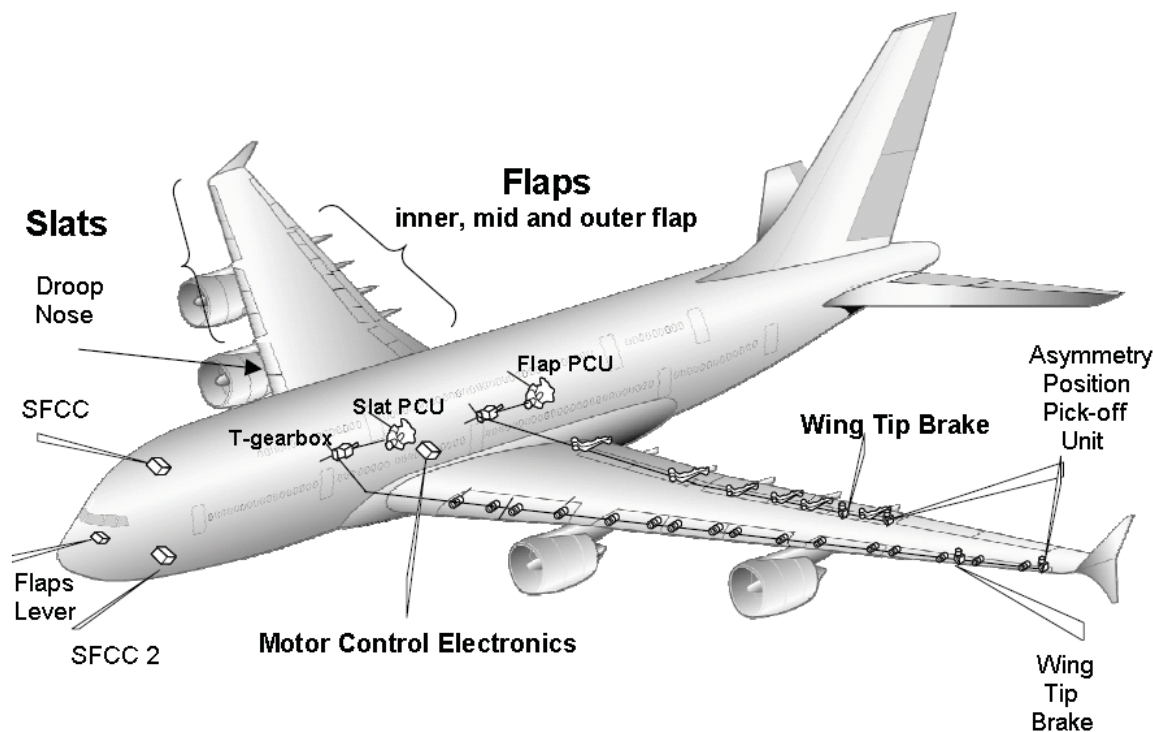
Assume that a certain structural component may contain cracks but **none** are larger than a known minimum detectable length  $a_d$



Periodic Inspections are needed  $\longrightarrow$  Damage Tolerant Design

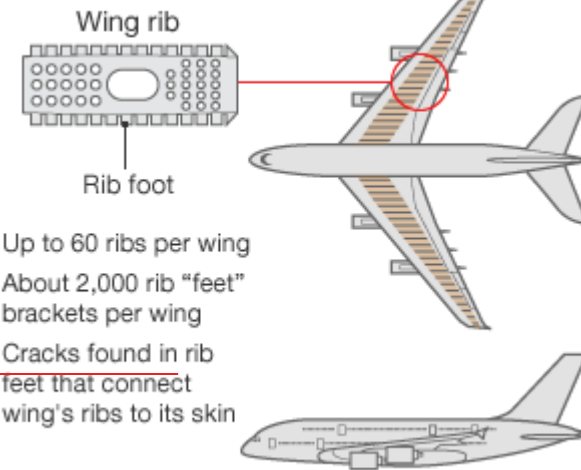


# Need for Crack Growth Analysis



A380 Wing Controls

Airbus A380: wing structure



Up to 60 ribs per wing  
About 2,000 rib "feet"  
brackets per wing  
Cracks found in rib  
feet that connect  
wing's ribs to its skin

Source: Airbus

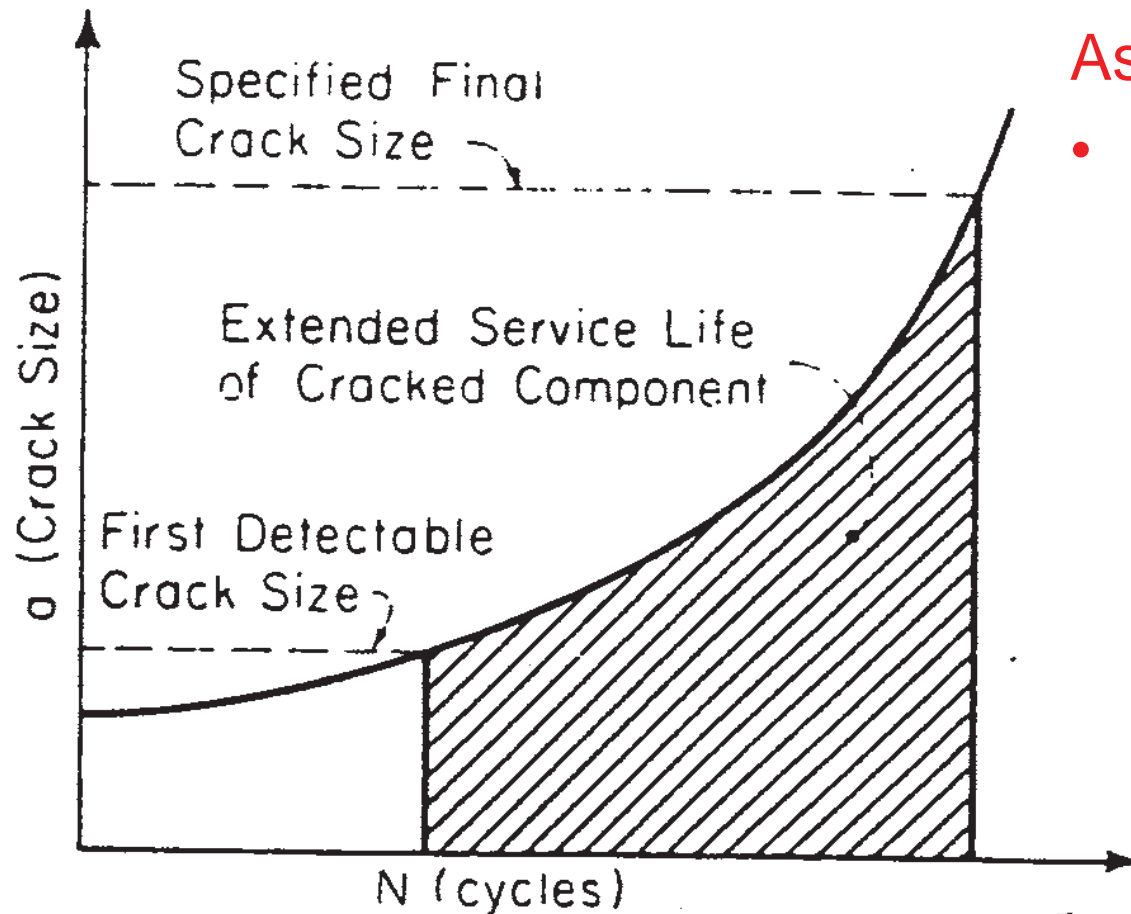
## Remaining Life Calculation



- Repair
- Ignore
- Replace
  - Now or
  - Latter

# Fatigue Crack Growth

a vs. N curve



Assume

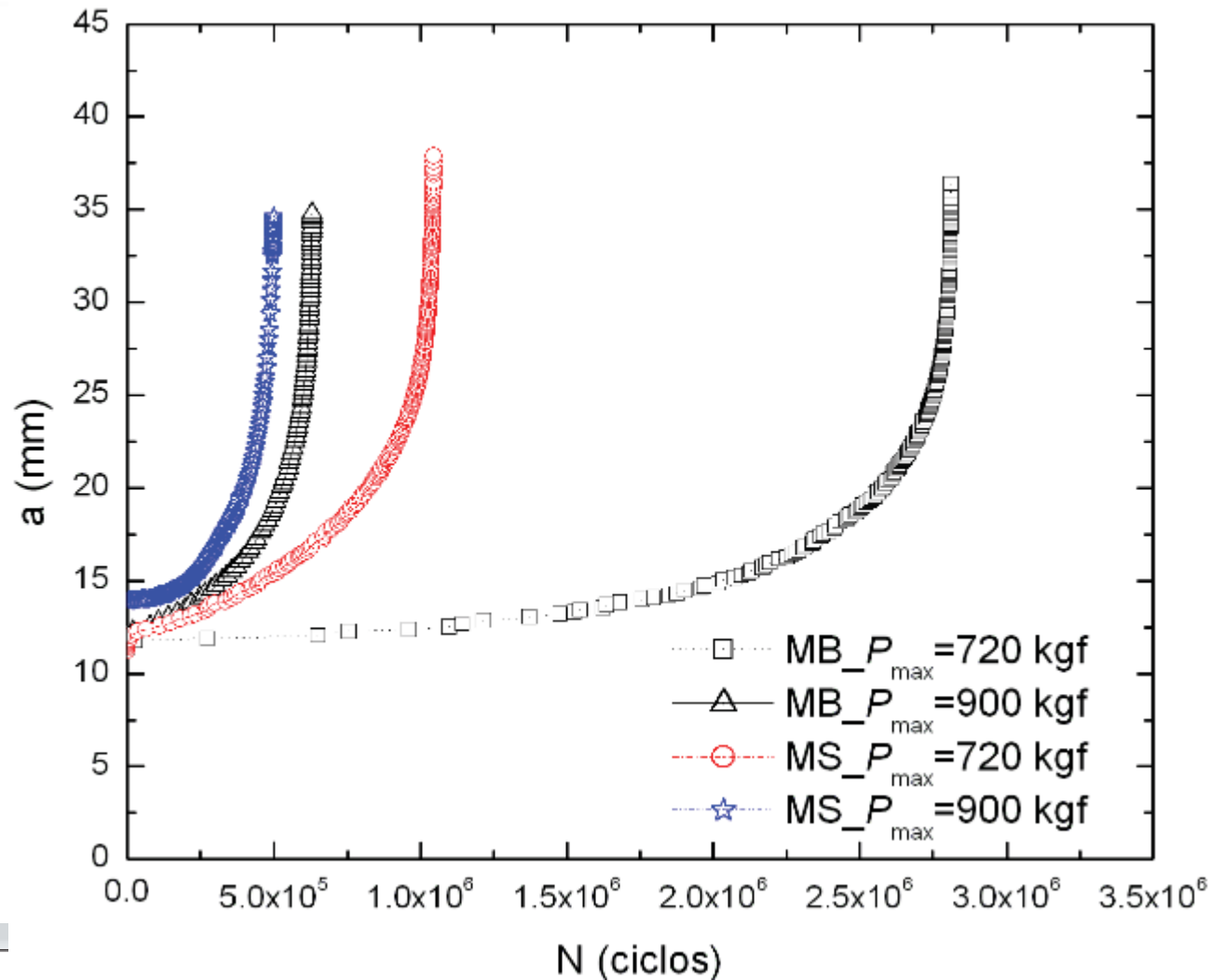
- constant cyclic loading

$$\Delta S = S_{\max} - S_{\min}$$

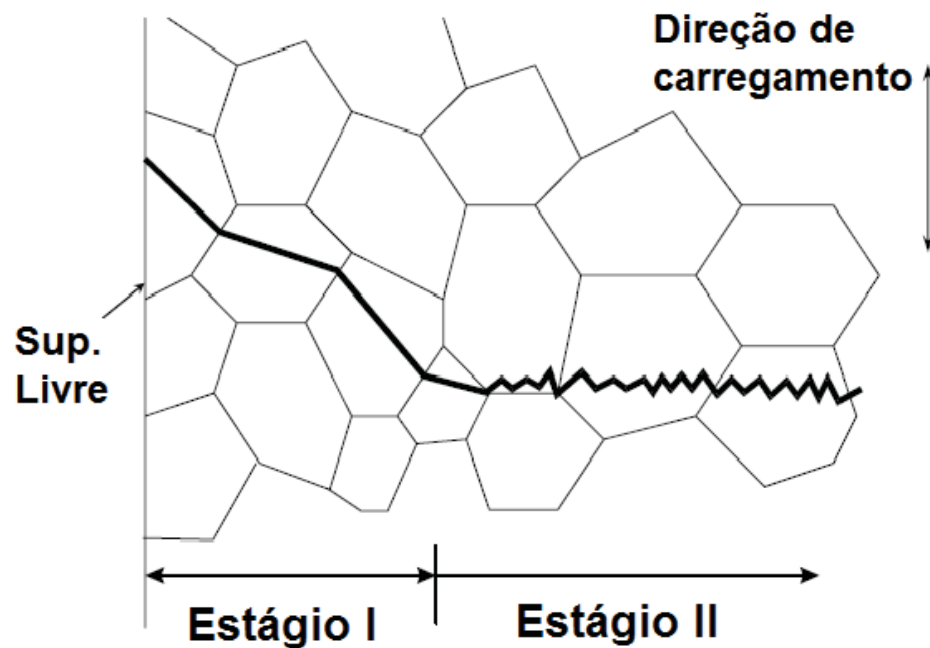
$$R = \frac{S_{\min}}{S_{\max}}$$

$$\Delta K = [F] \Delta S \sqrt{\pi a}$$

# Taxas Experimentais de Crescimento de Trinca por Fadiga



# Propagação de Trinca



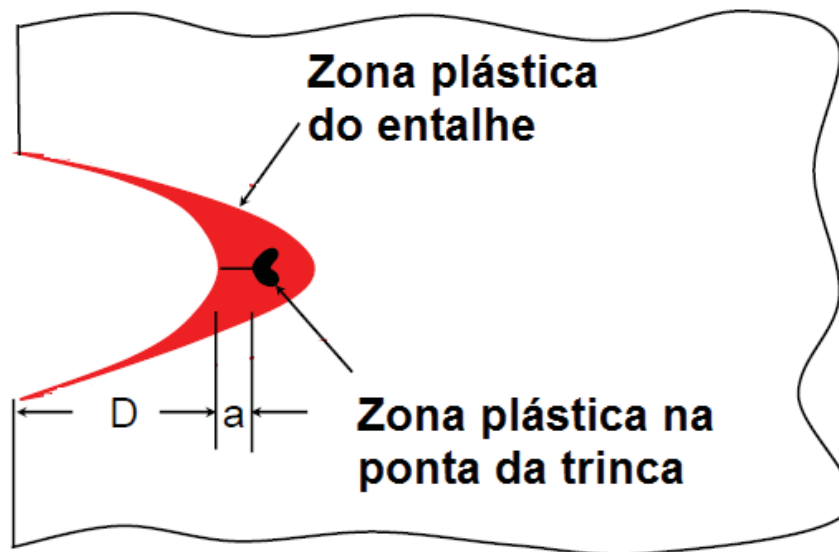
Estágio I de Propagação



Estágio II de Propagação

# Propagação de Trinca

- Estágio I



- Tamanho ( $a$ )  $\sim$  2-4 grãos ( $D$ )

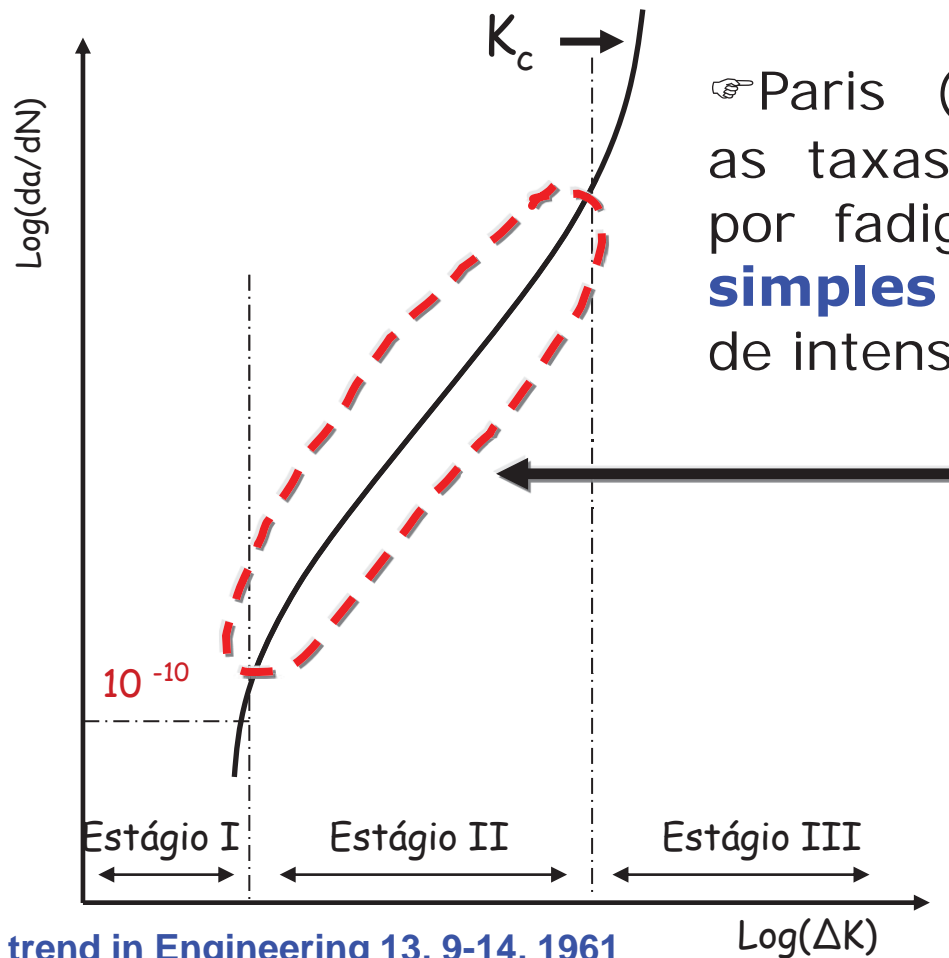
- Fortemente influenciada pela microestrutura

- Planos de escorregamento

- Nível de tensão

- Plasticidade na ponta da trinca

# Propagação de Trincas (Estágio II)



Paris (1961) propus caracterizar as taxas de crescimento de trinca por fadiga - em forma **elegante** e **simples** - por meio do fator elástico de intensidade de tensões  $K$ :

$$\frac{da}{dN} = C (\Delta K)^m$$

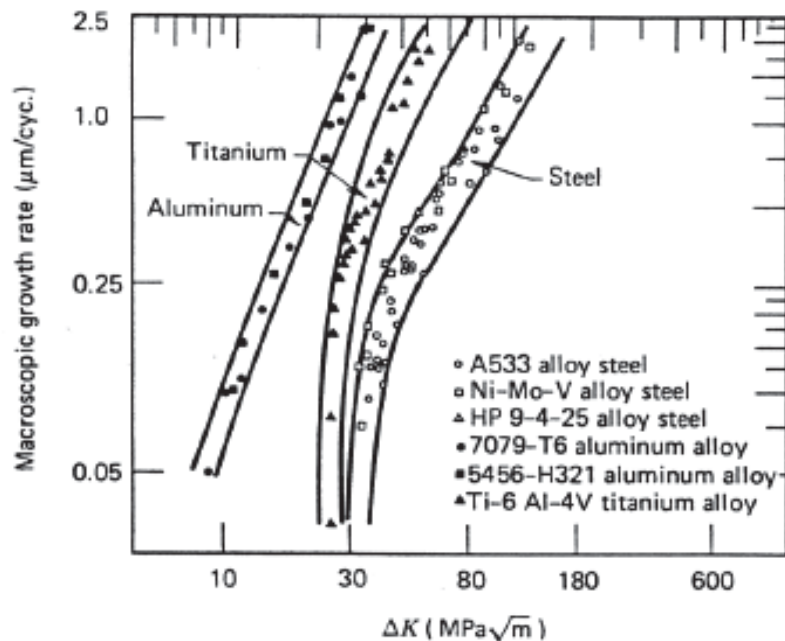
$$\Delta K = \xi \Delta \varepsilon_{ij}$$

$$\xi = \left( \frac{E \sqrt{2\pi r}}{f_{ij}(\theta)} \right)$$

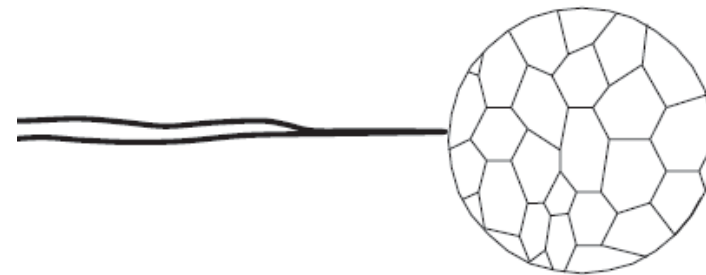
The trend in Engineering 13, 9-14, 1961

# Propagação de Trincas (Estágio II)

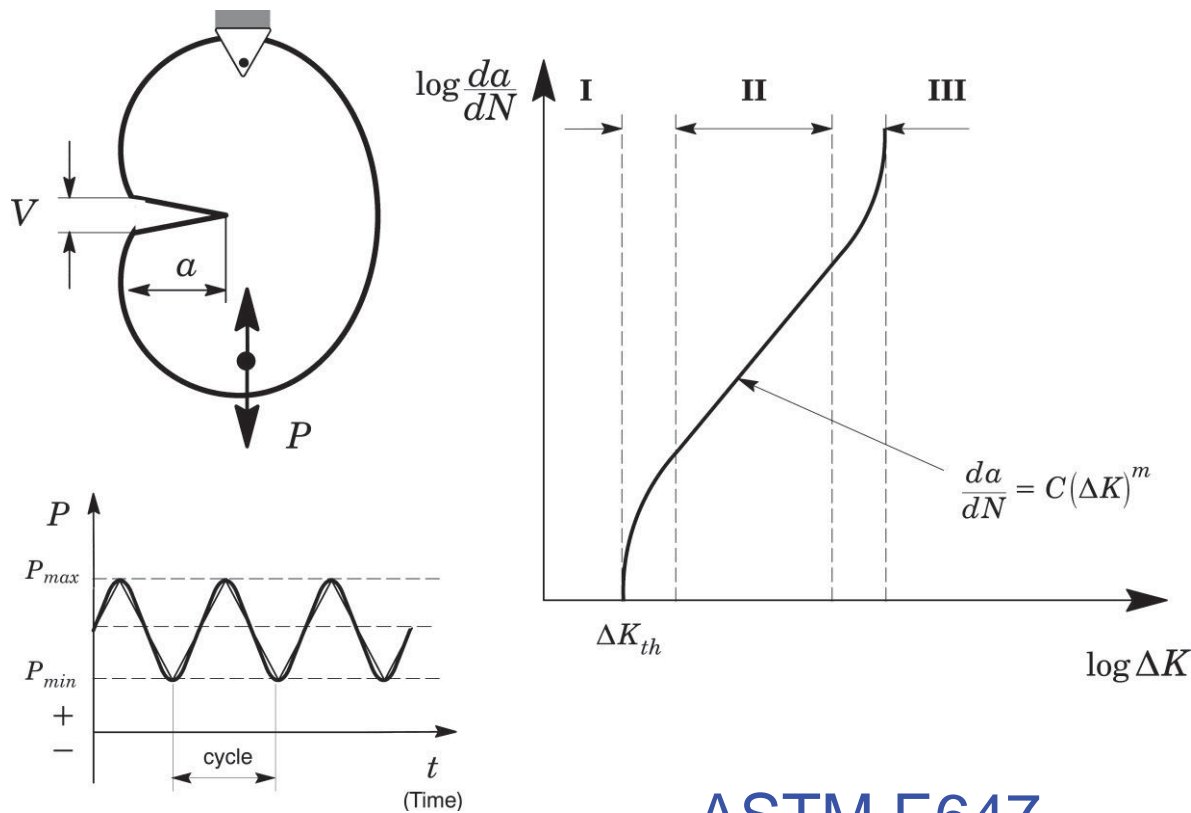
- Pouca influencia da resistência do material



- Zona plástica  $\gg$  microestrutura do material (pouca influência da microestrutura)



# Avaliação Convencional das Propriedades da/dN



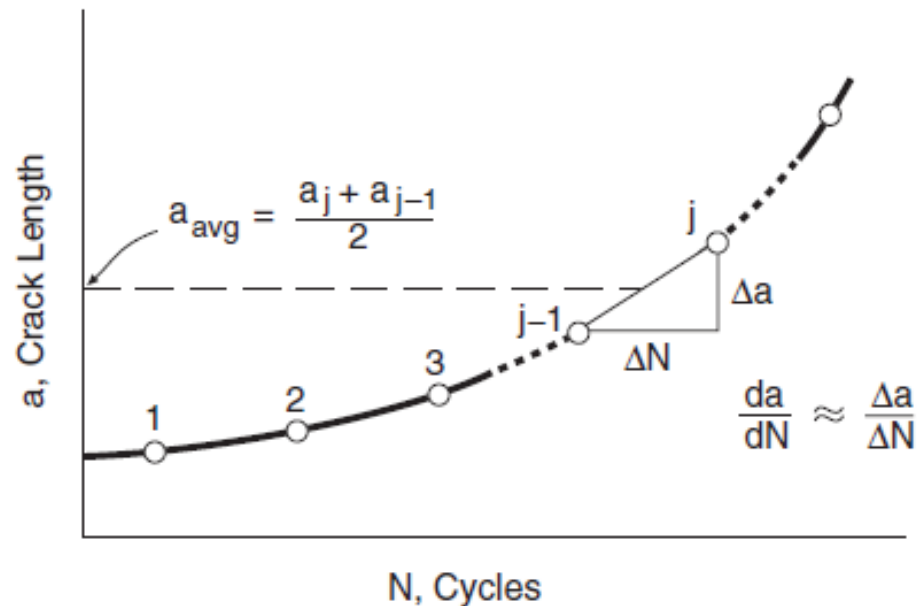
ASTM E647





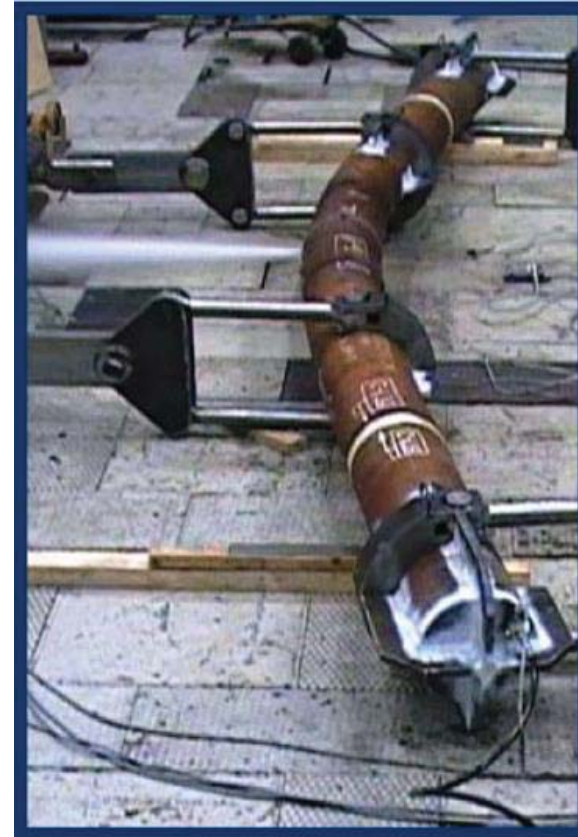
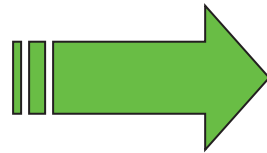
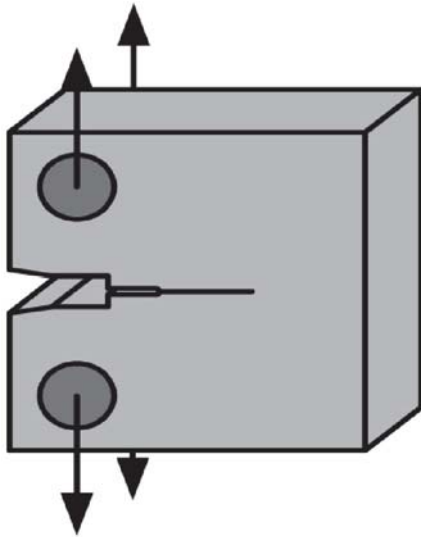
# Avaliação Convencional das Propriedades da/dN

ASTM E647



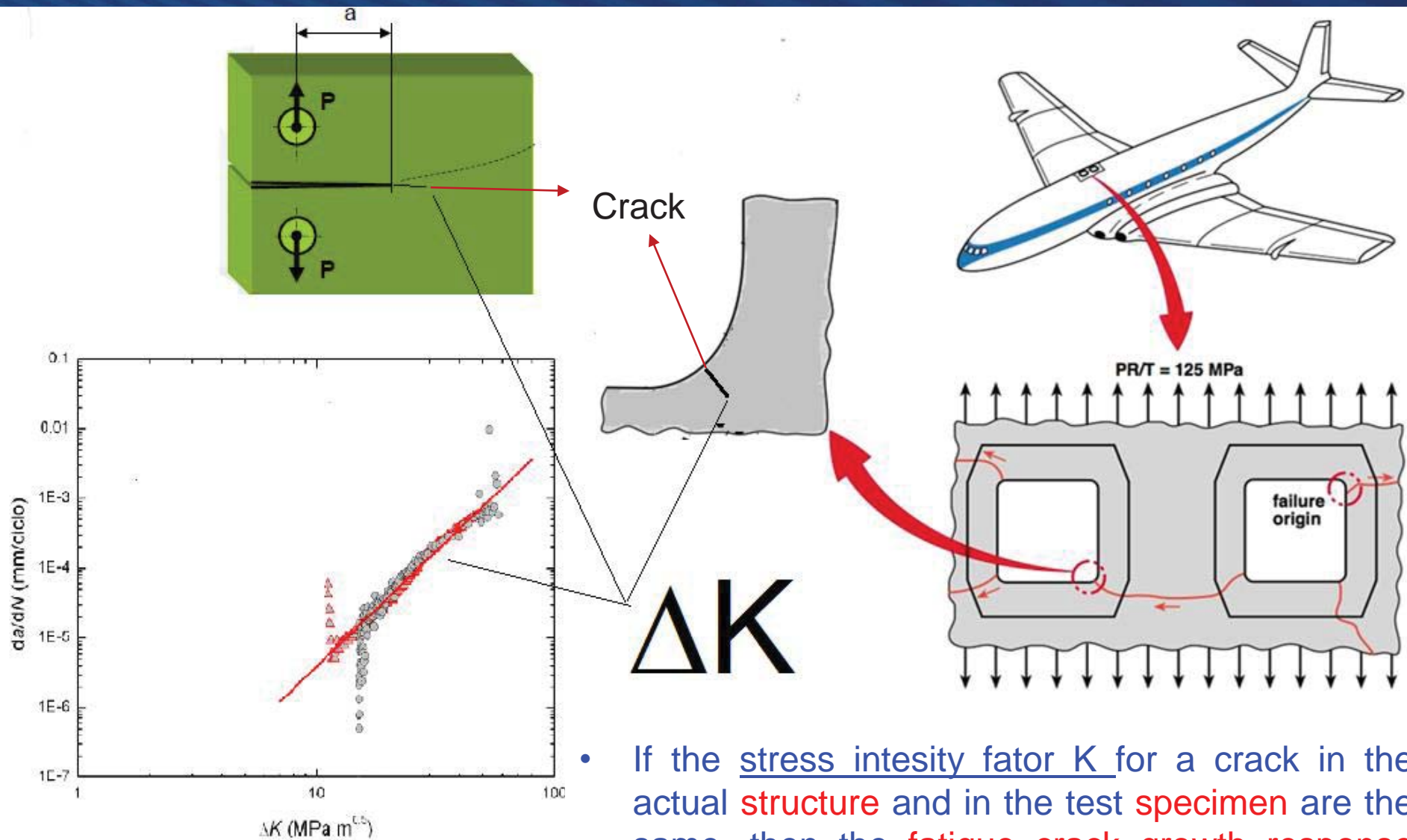
$$\left(\frac{da}{dN}\right)_j \approx \left(\frac{\Delta a}{\Delta N}\right)_j = \frac{a_j - a_{j-1}}{N_j - N_{j-1}} \quad \Delta K_j = F \Delta S \sqrt{\pi a_{avg}}$$

# Correlação Laboratório vs. Estrutura



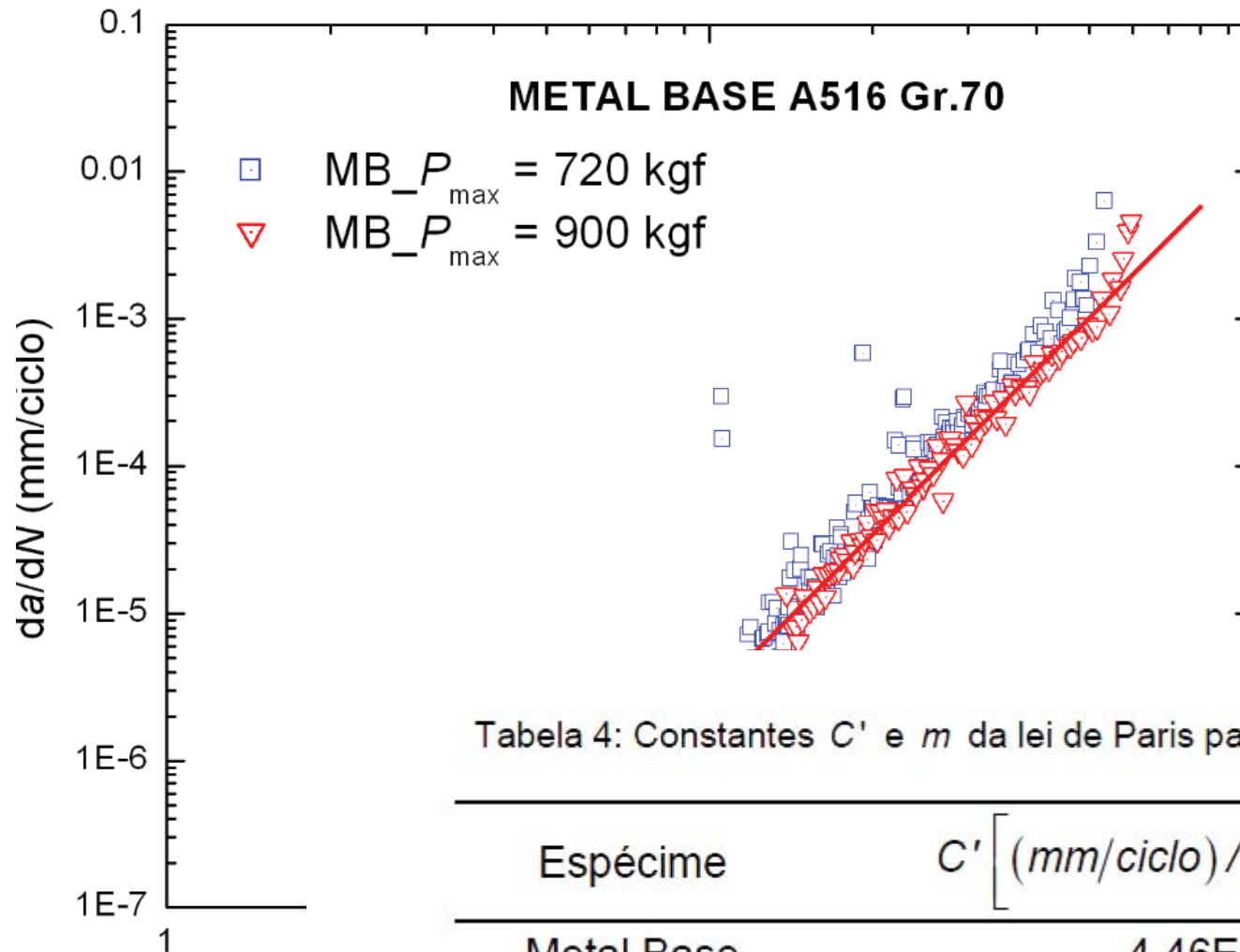
Similitude

# Princípio de Similaridade (Similitude)



- If the stress intensity factor  $K$  for a crack in the actual **structure** and in the test **specimen** are the same, then the **fatigue crack growth response** in each case will be the same and describe by the material  $da/dN$ - $\Delta K$  curve.

# Taxas Experimentais de Crescimento de Trinca por Fadiga

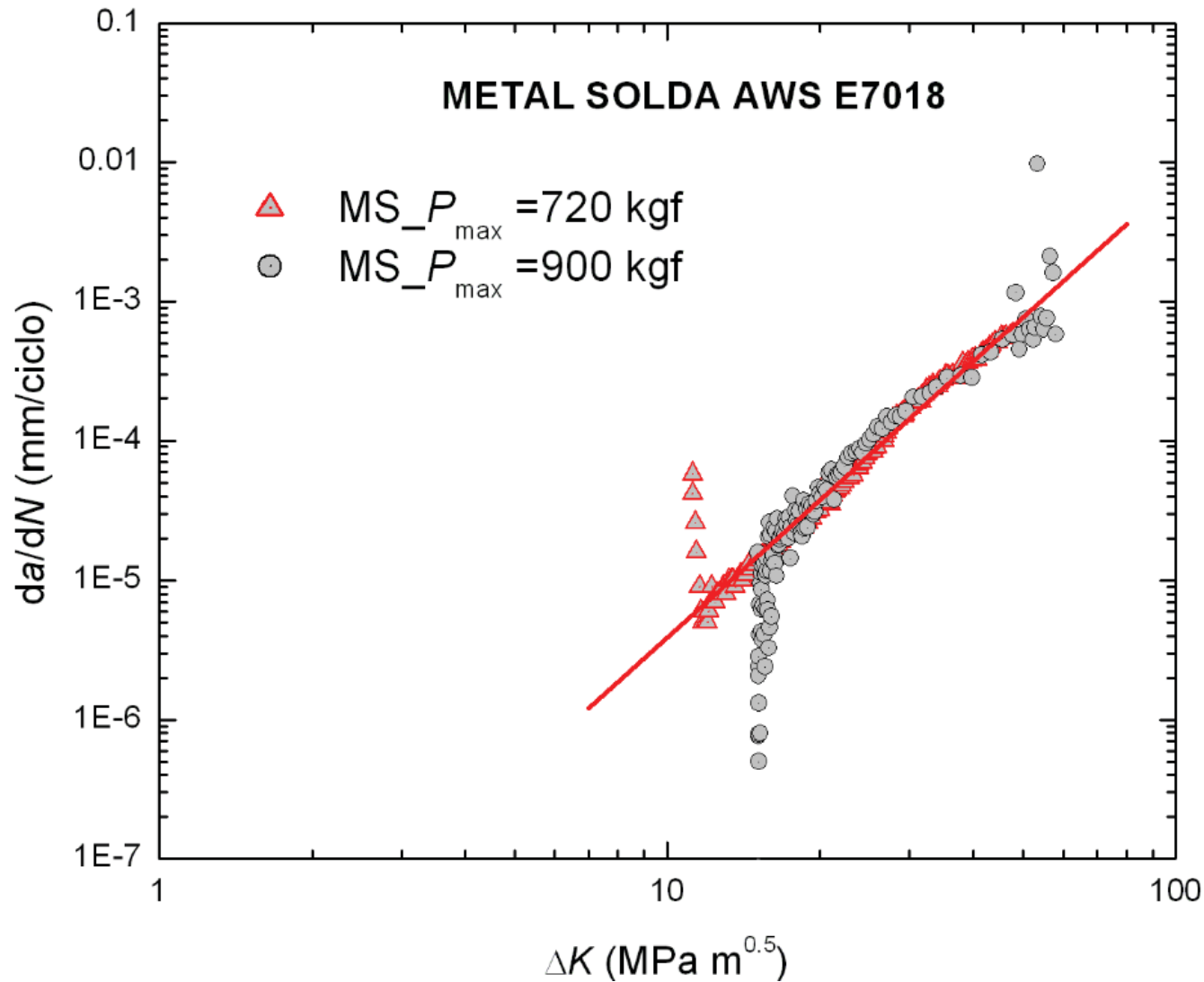


Metal Base

Tabela 4: Constantes  $C'$  e  $m$  da lei de Paris para o metal base o metal de solda

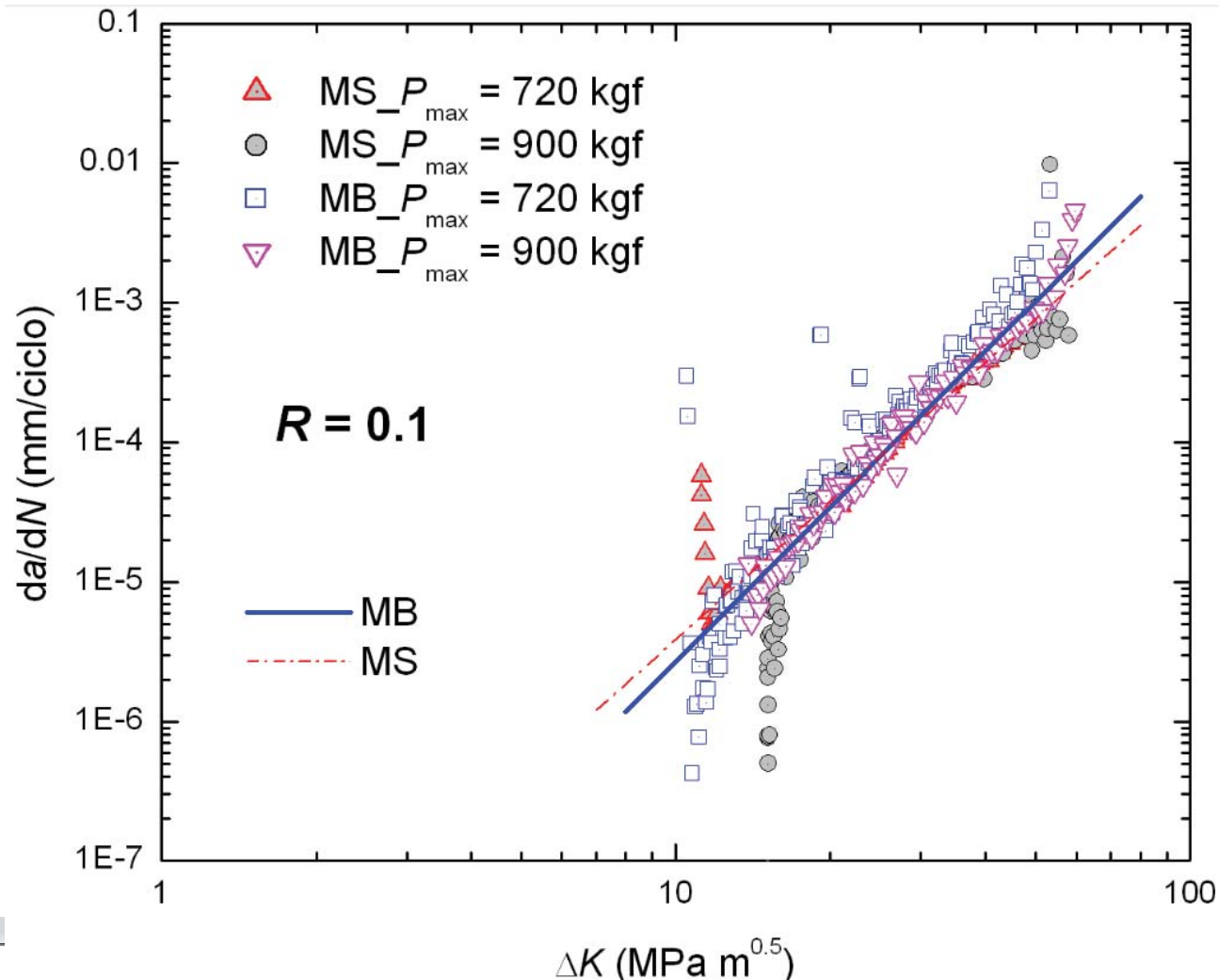
Espécime	$C' \left[ (mm/ciclo) / (MPa\sqrt{m})^m \right]$	$m$
Metal Base	4.46E-10	3.85
Metal Solda	1.92E-9	3.34

# Taxas Experimentais de Crescimento de Trinca por Fadiga



Metal Solda

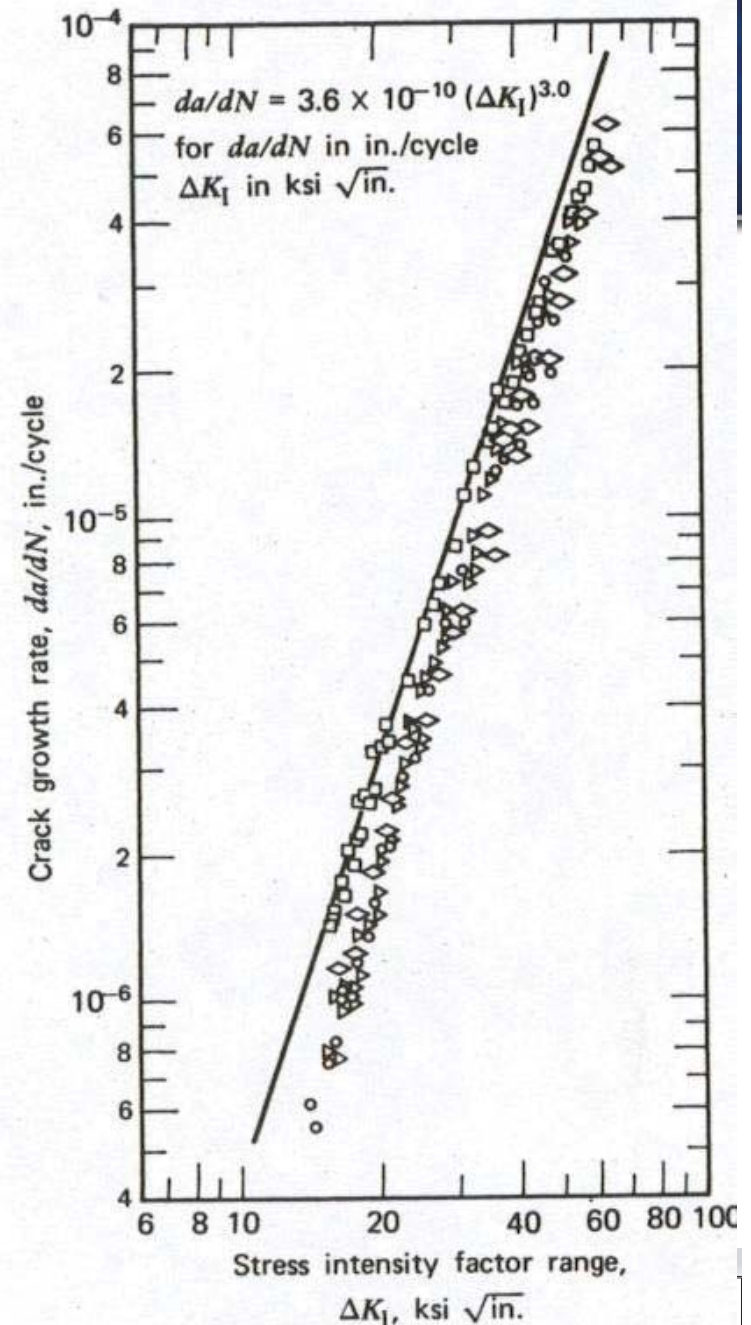
# Taxas Experimentais de Crescimento de Trinca por Fadiga



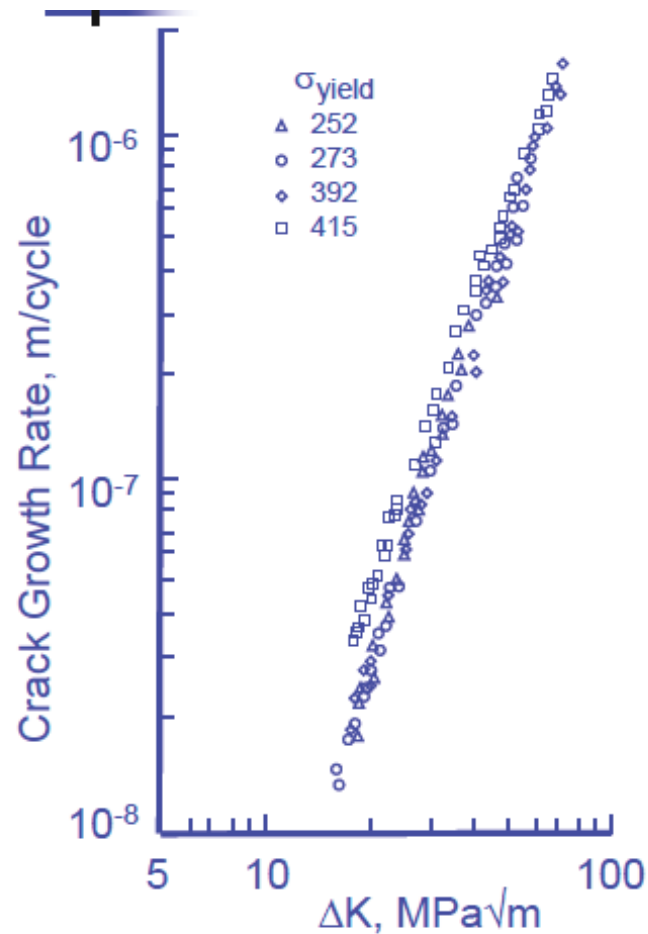
# Crack Growth Data

Barsom has evaluated Paris equation (for region II) for a wide variety of steels varying in yield strength from 250 to 2070 MPa (36 to 300 ksi).

- He shows that the scatter band for a given  $\Delta K$ , with many **ferritic-pearlitic steels**, varies by a factor of about 2 (shown in



# Crack Growth Data



Ferritic-Pearlitic Steel:

$$\frac{da}{dN} = 6.9 \times 10^{-12} (\Delta K \text{ MPa}\sqrt{\text{m}})^{3.0}$$

Martensitic Steel:

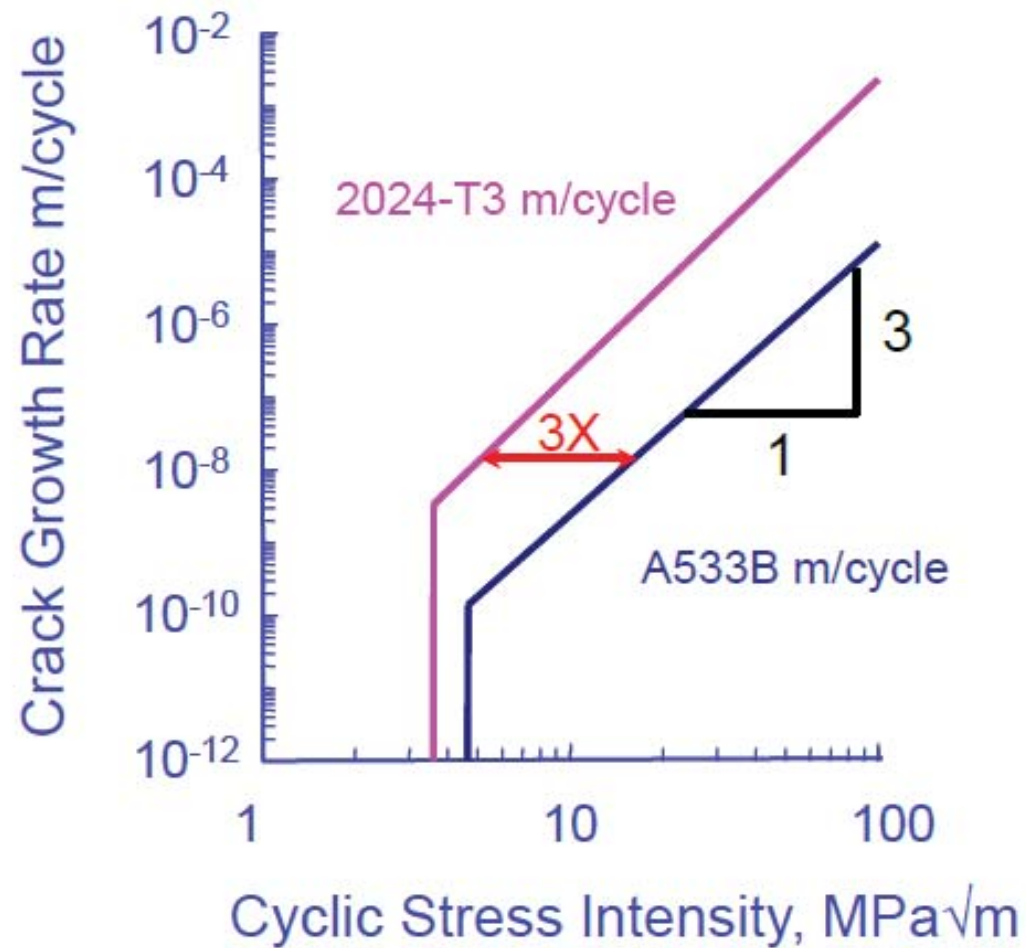
$$\frac{da}{dN} = 1.4 \times 10^{-10} (\Delta K \text{ MPa}\sqrt{\text{m}})^{2.25}$$

Austenitic Stainless Steel:

$$\frac{da}{dN} = 5.6 \times 10^{-12} (\Delta K \text{ MPa}\sqrt{\text{m}})^{3.25}$$

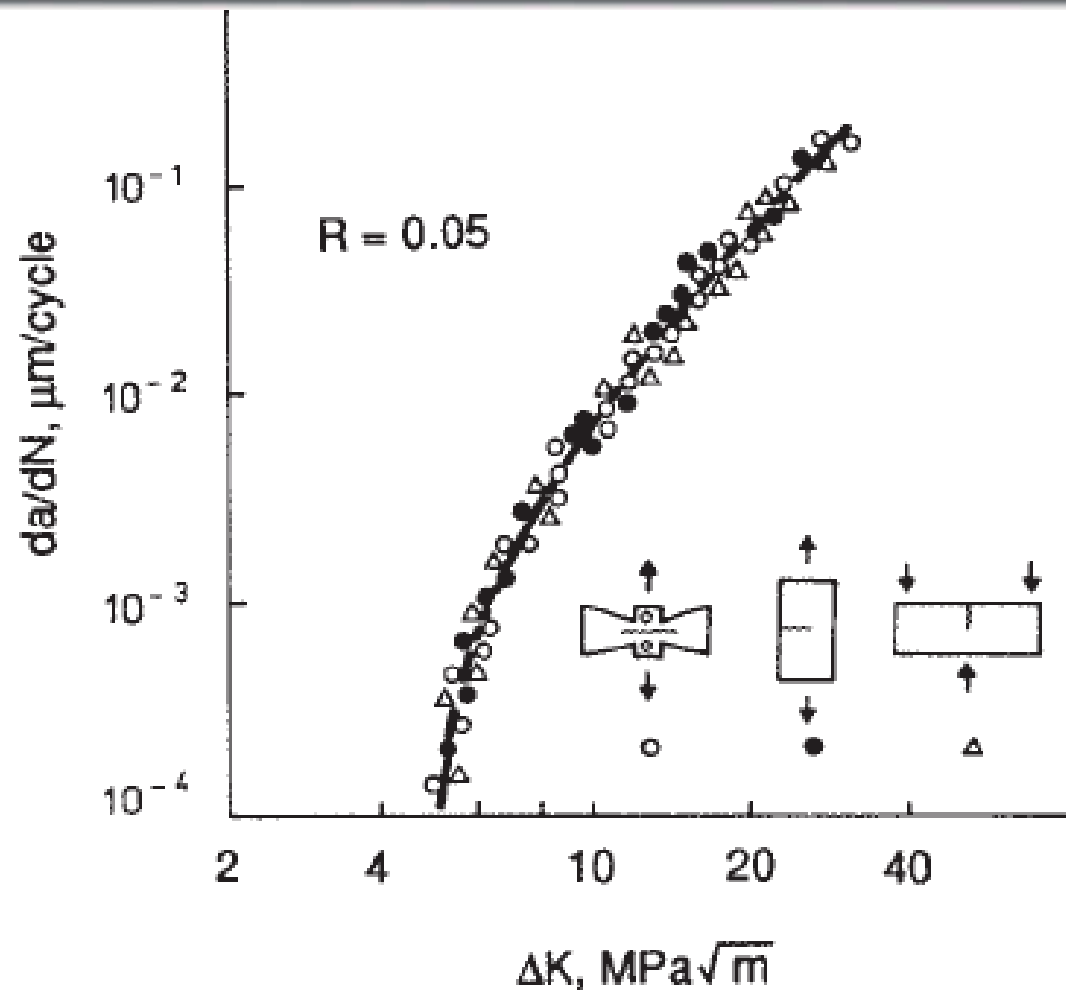


# Crack Growth Data

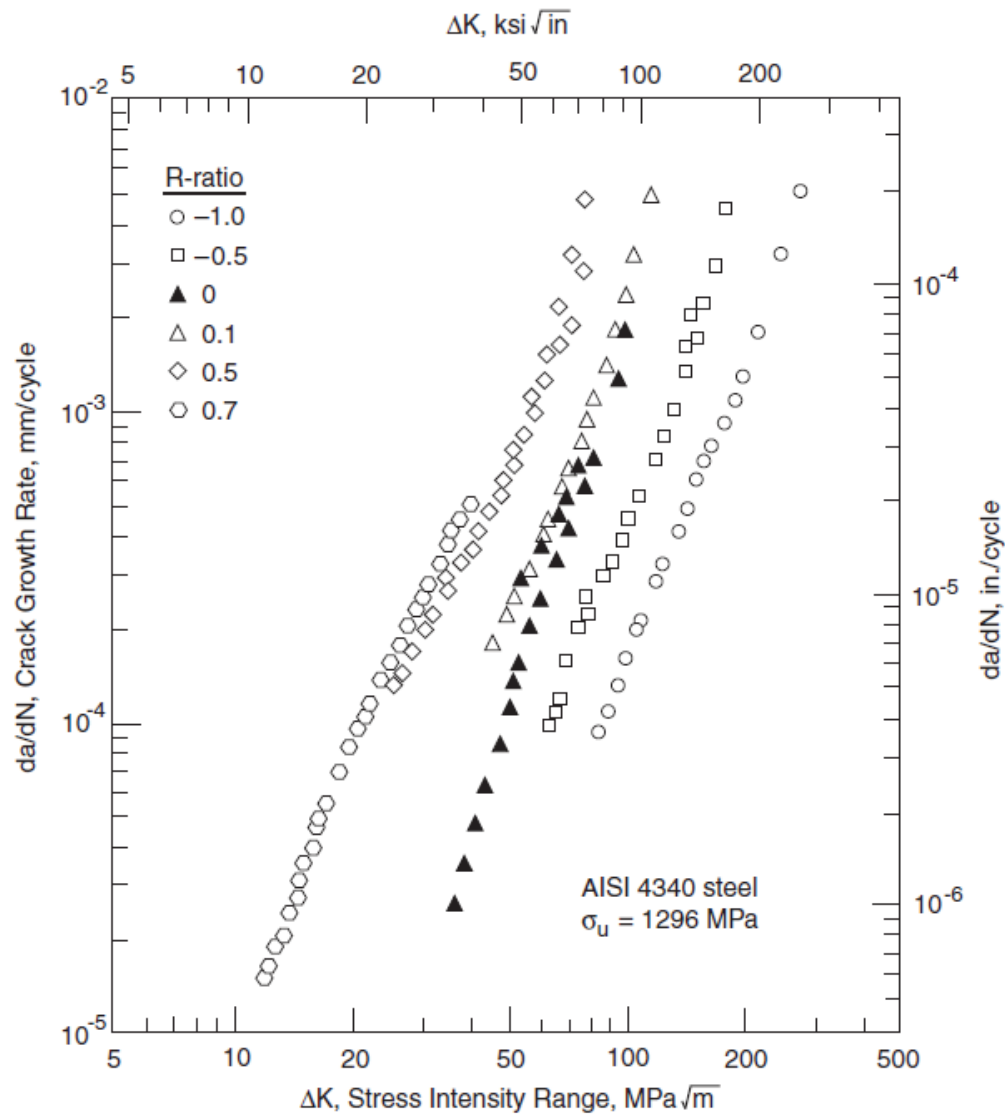


Steel welds are 3 times stronger than aluminum

# Geometry Independence

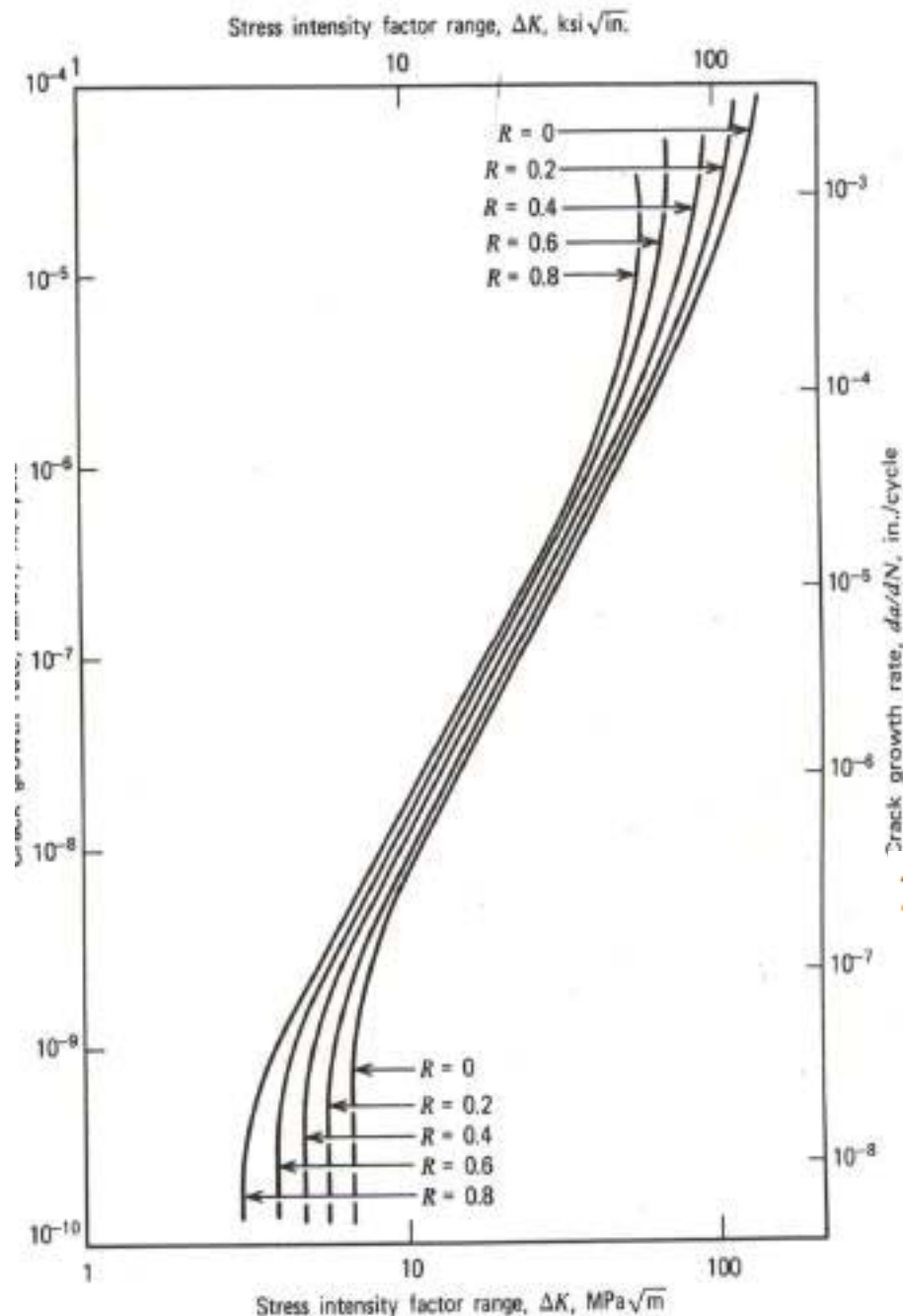


# Stress Ratio Effects



## Mean Stress Effects

# Stress Ratio Effects



The effect of R on fatigue crack growth is very material dependent.

## The Walker Equation

$$\overline{\Delta K} = \frac{\Delta K}{(1 - R)^{1-\gamma}}$$

$\gamma$  is a constant for the material and  $\overline{\Delta K}$  is an equivalent zero-to-tension ( $R = 0$ )

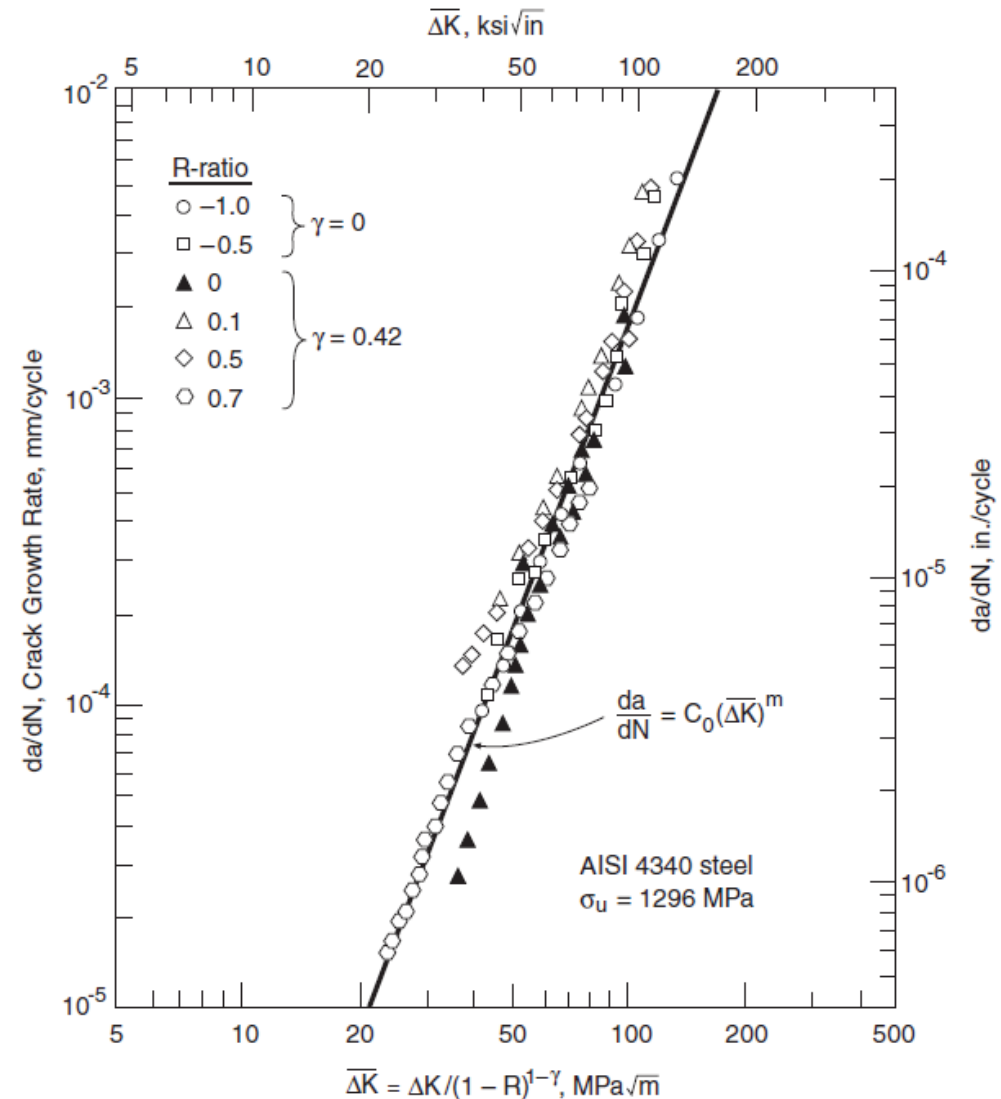
$$\frac{da}{dN} = C_0 \left[ \frac{\Delta K}{(1 - R)^{1-\gamma}} \right]^m$$

# Stress Ratio Effects

## The Walker Equation

$$\overline{\Delta K} = \frac{\Delta K}{(1 - R)^{1-\gamma}}$$

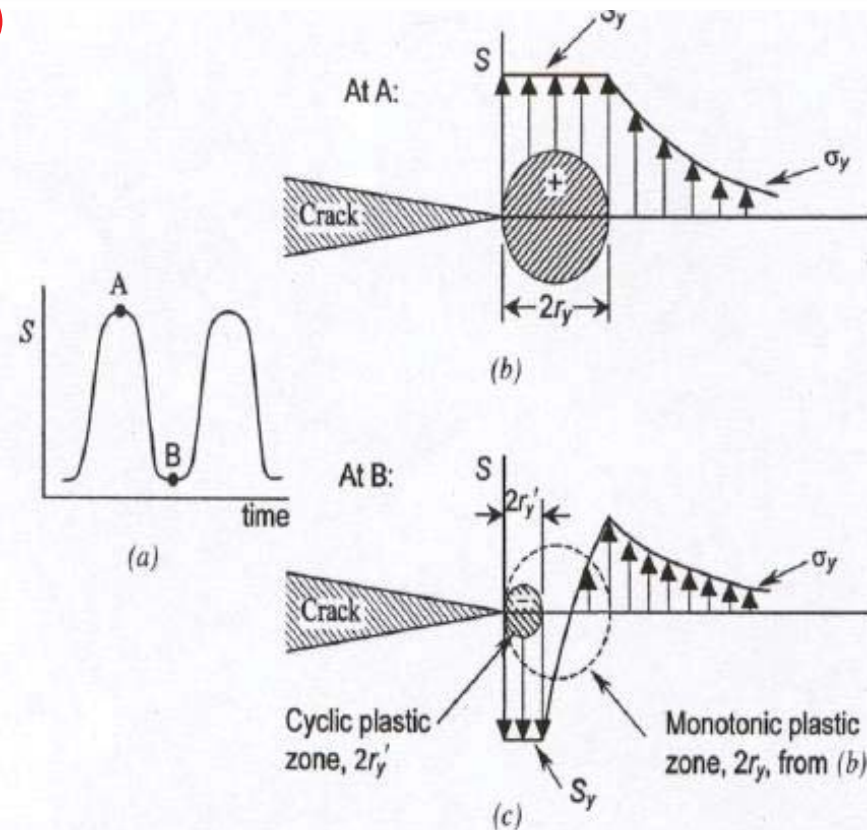
$$\frac{da}{dN} = C_0 \left[ \frac{\Delta K}{(1 - R)^{1-\gamma}} \right]^m$$



# Plastic Zone Size

## Reversed Plastic Zone Size (Cyclic)

- A key point to recognize is that the sign of the inelastic stress distribution associated with the cyclic plastic zone size is opposite to the sign of the applied stress during loading.
- Thus, if a region yields in tension during loading, as shown in Fig. 6.18(b), after unloading a portion of that region is in compression, as shown in Fig. 6.18(c).



**Figure 6.18** Schematic of the plastic zone at the tip of an advancing crack. (a) Loading cycle. (b) Monotonic plastic zone. (c) Cyclic plastic zone.

# Others Factors Effects

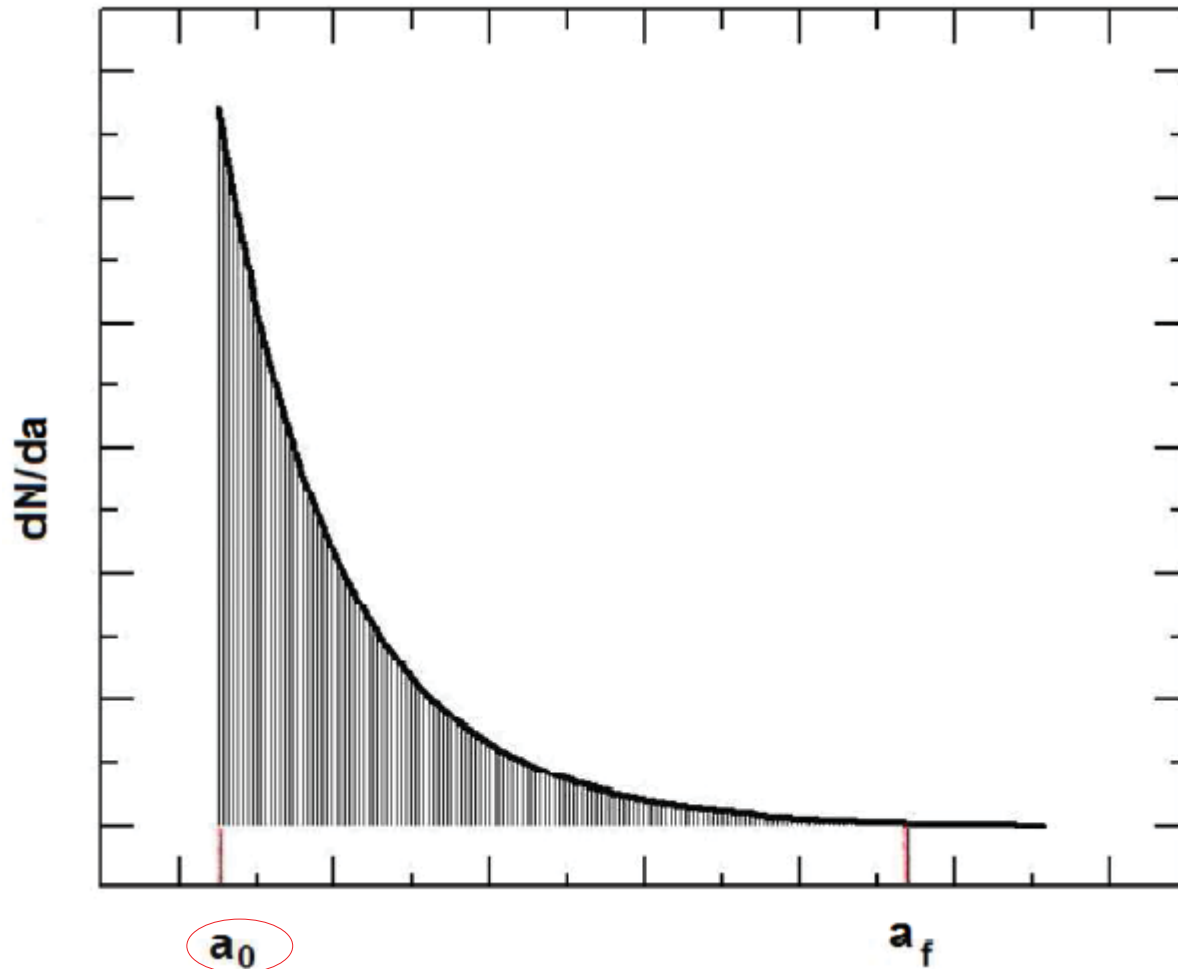
Frequency, wave shape, and thickness effects on constant amplitude fatigue crack growth rates are secondary compared to environmental effects such as corrosion and temperature.

# AGENDA

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# Life Estimation



Integration of FCGR

$$N_f = \int_{a_0}^a \frac{da}{C \Delta K^m}$$

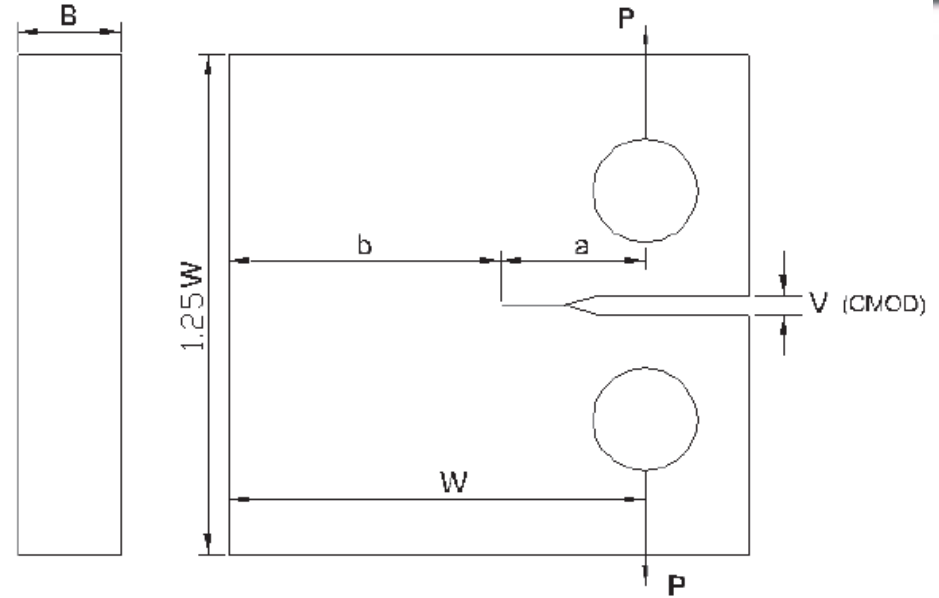
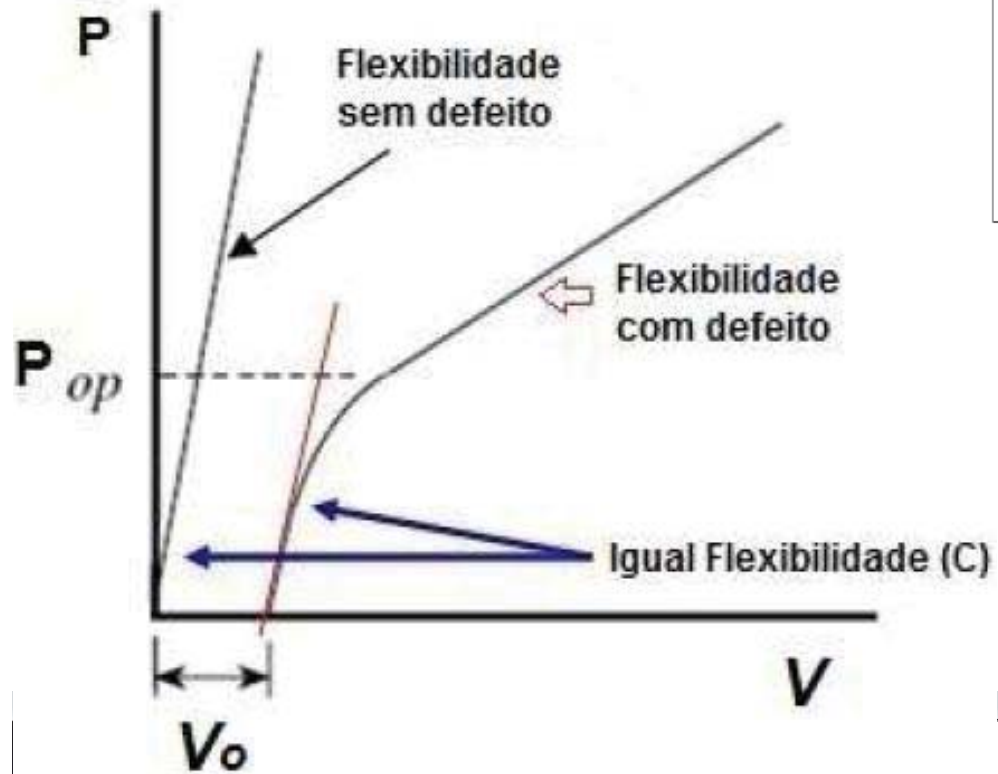
Take into account:

- R-ratio effects

Prediction is very sensitive to the initial crack length

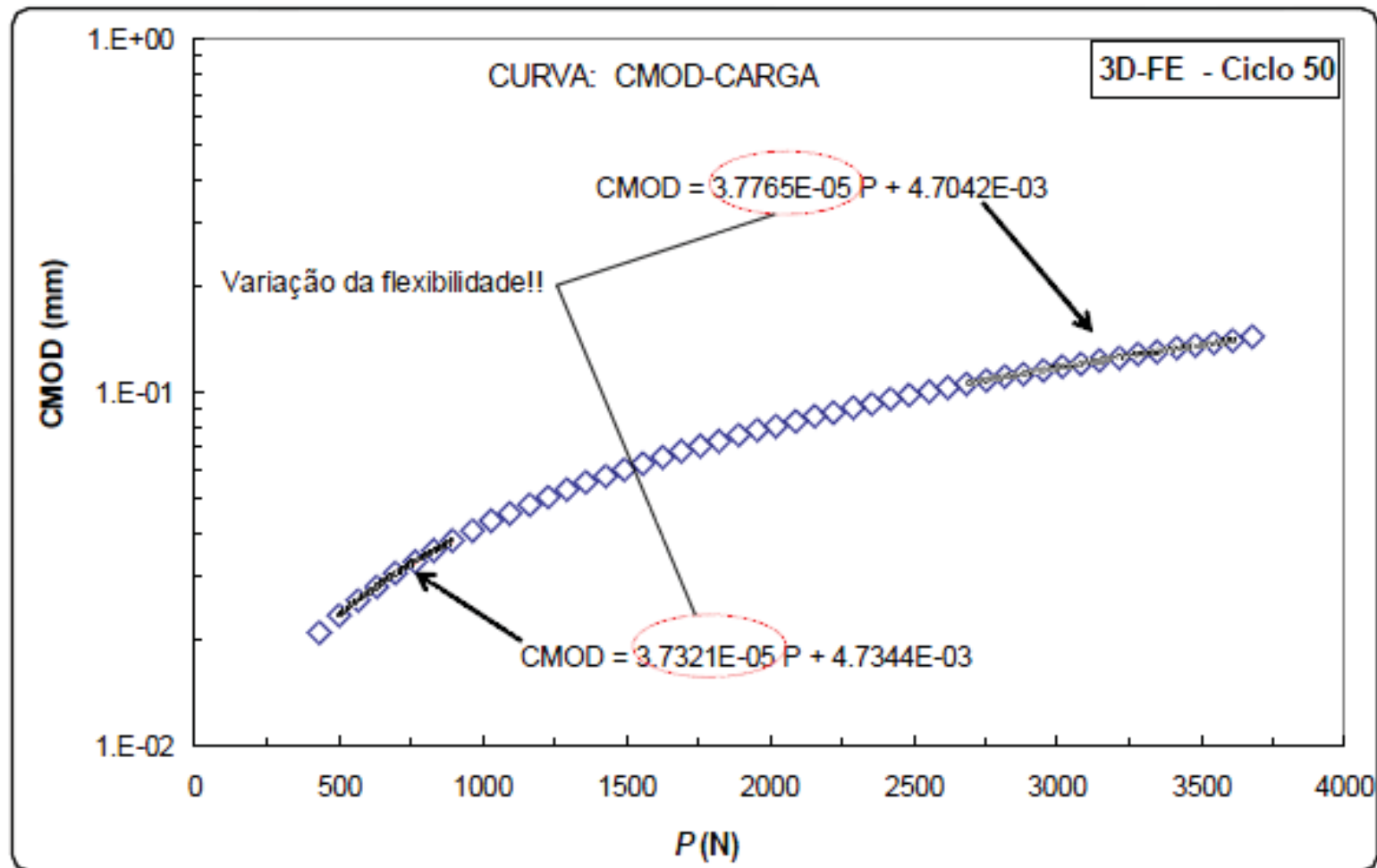
# Crack Closure

Elber 1970



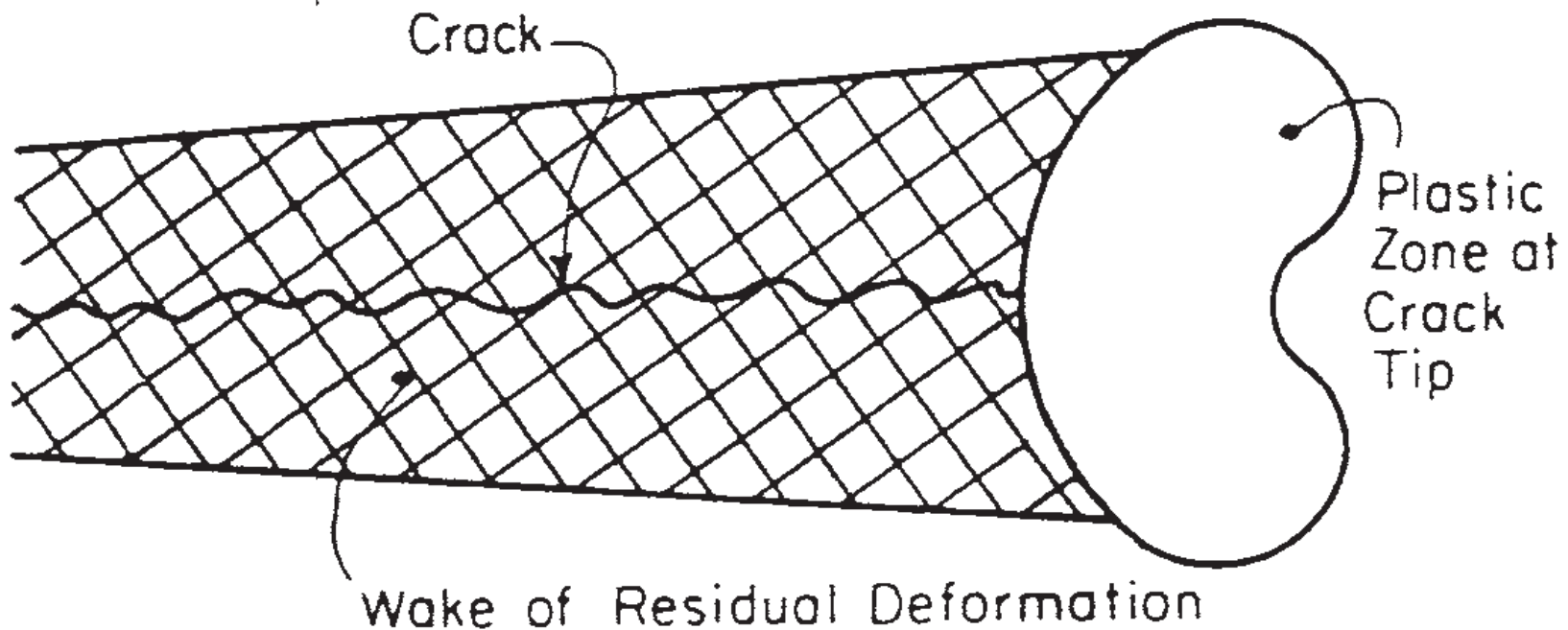
# Fatigue Crack Growth Behavior

## Fechamento de Trinca



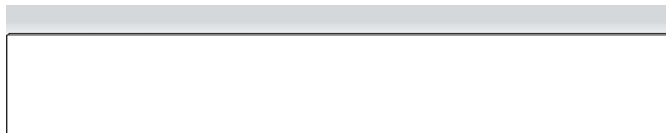
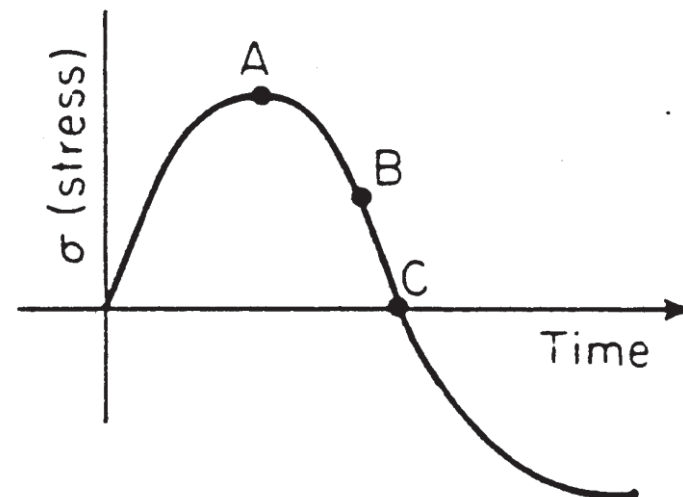
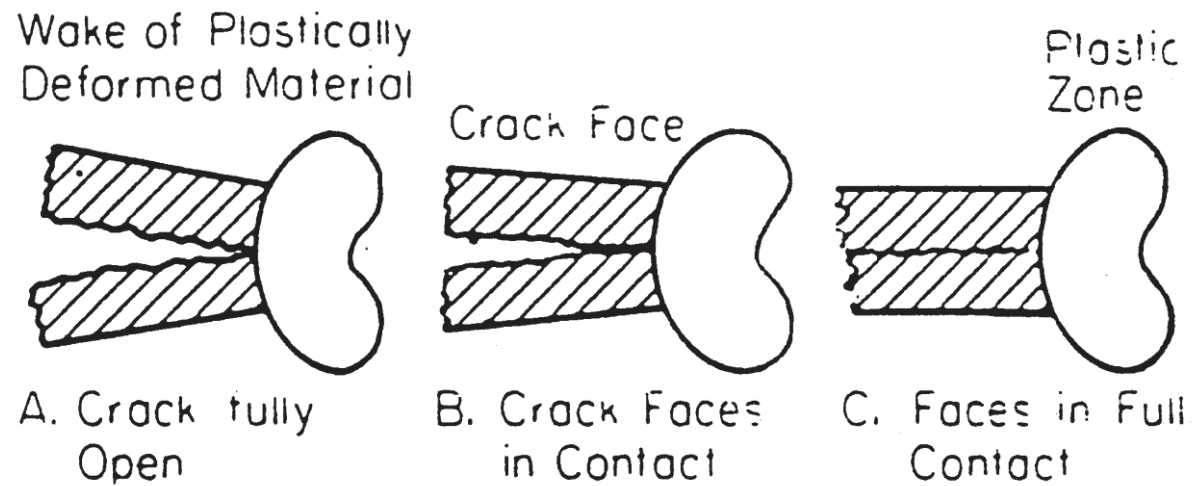
# Fatigue Crack Growth Behavior

## Fechamento de Trinca



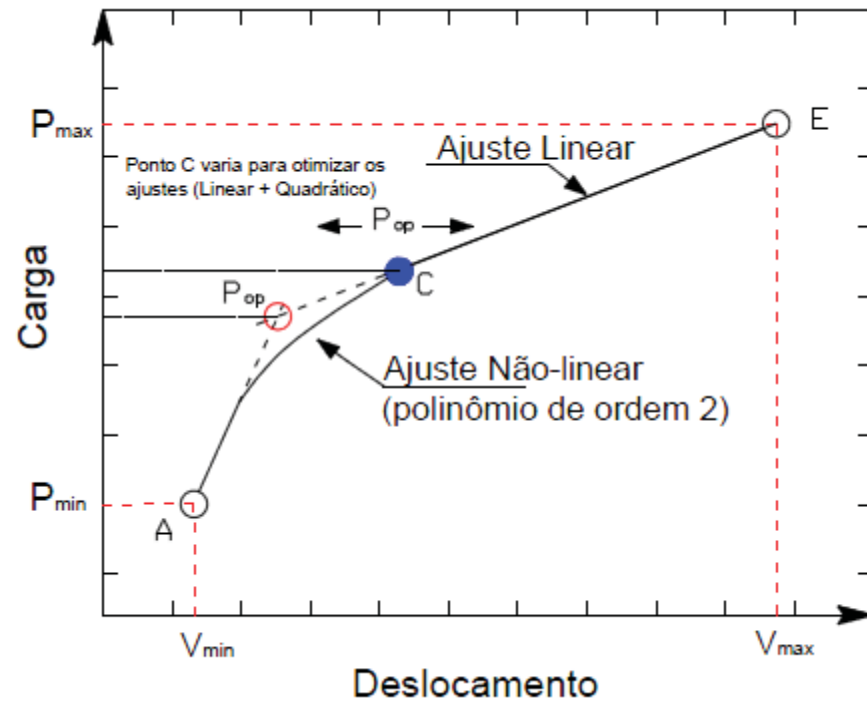
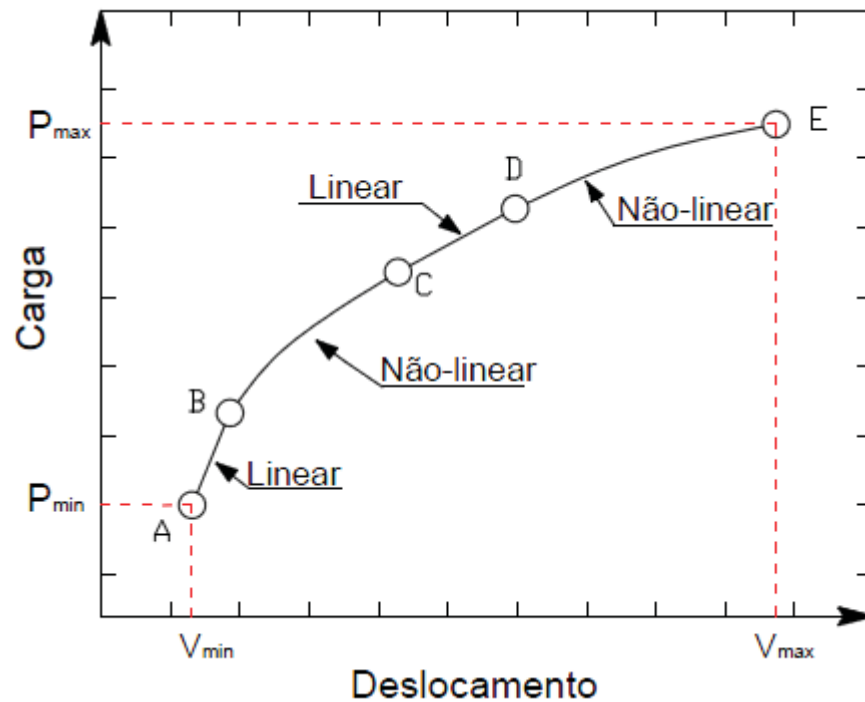
# Fatigue Crack Growth Behavior

## Fechamento de Trinca

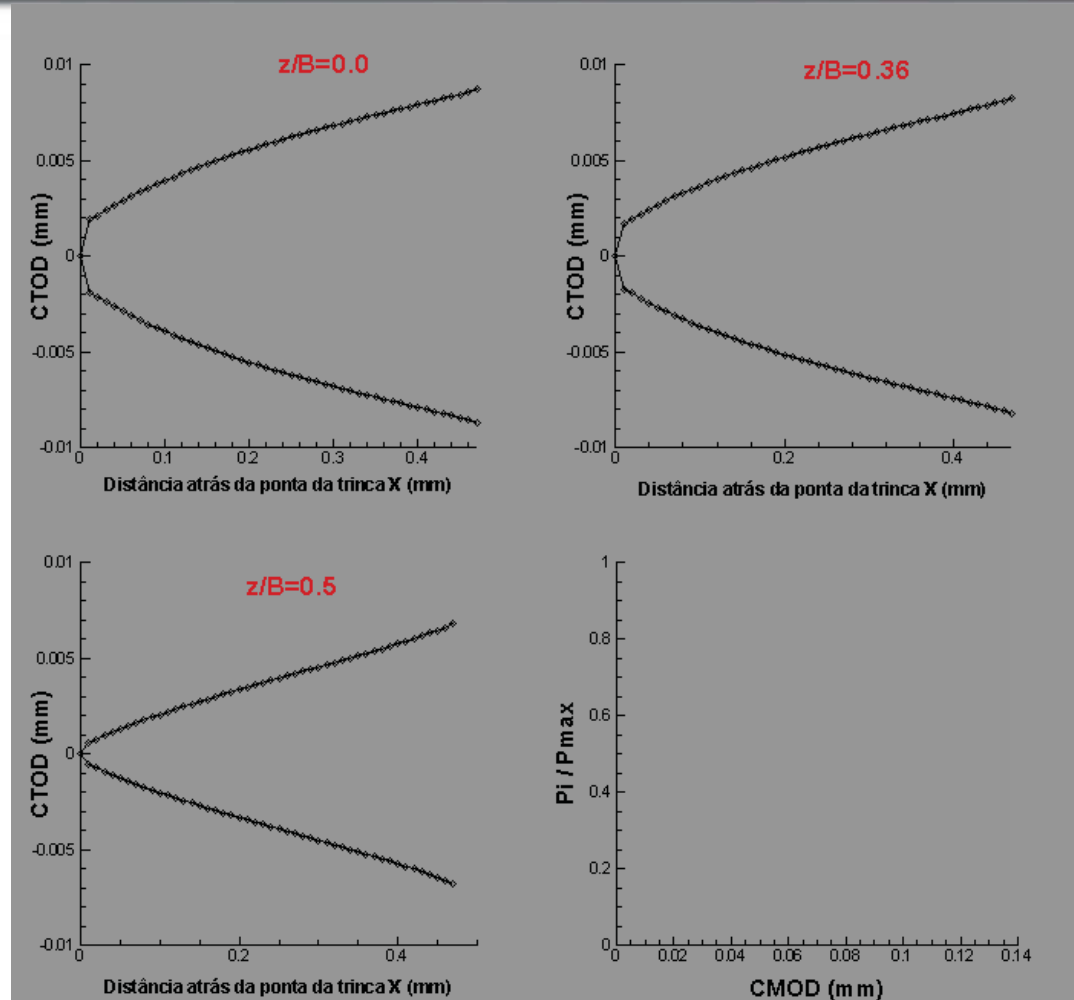
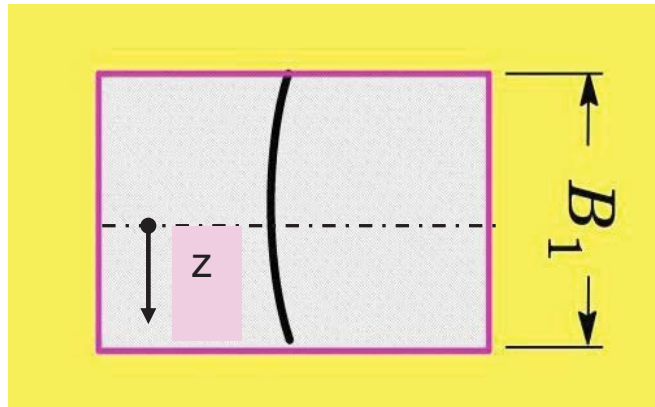


# Fatigue Crack Growth Behavior

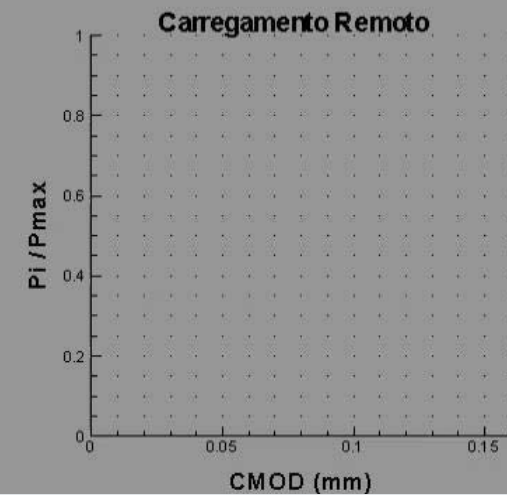
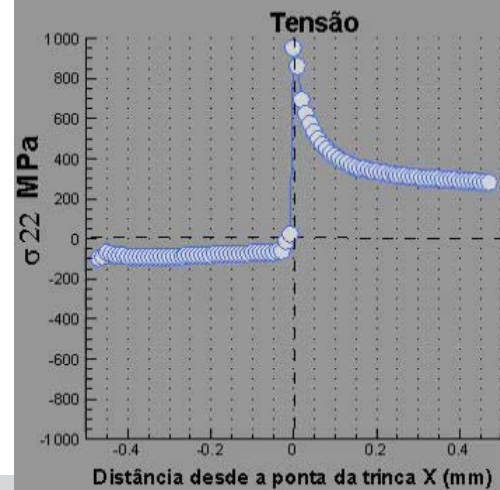
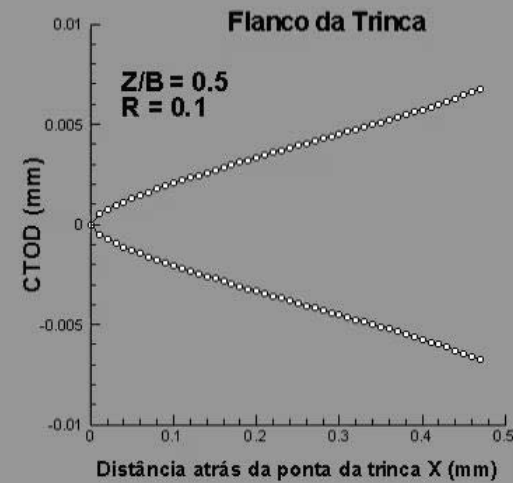
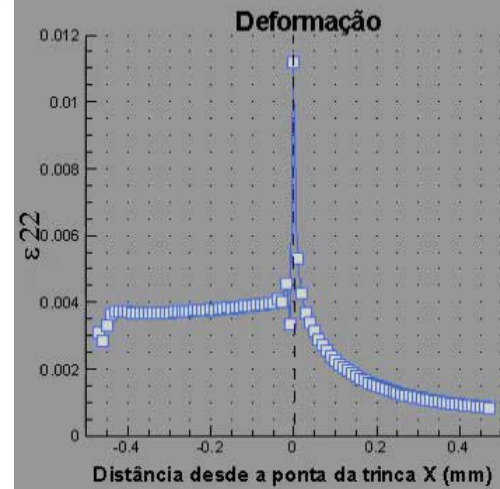
## Fechamento de Trinca



# Fechamento de Trinca por Plasticidade

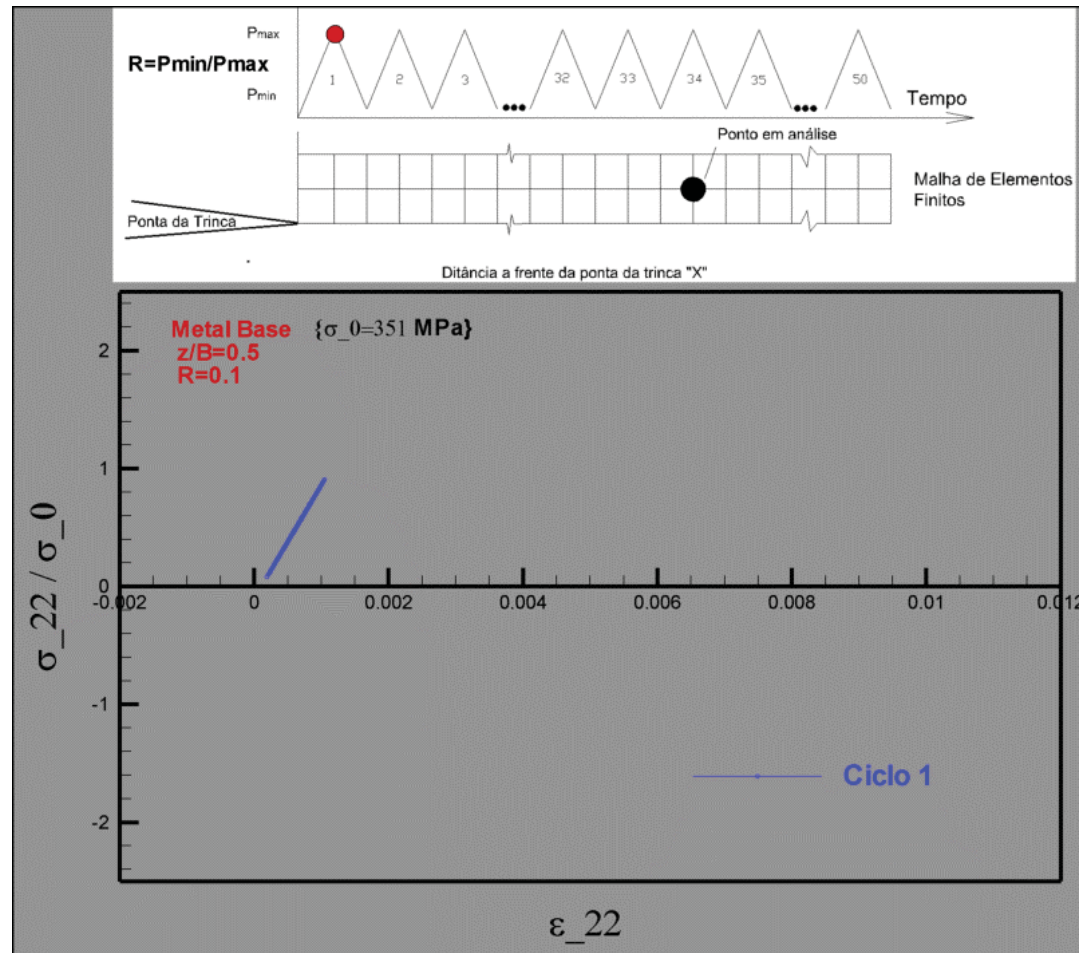


# Crack Closure induced by Plasticity



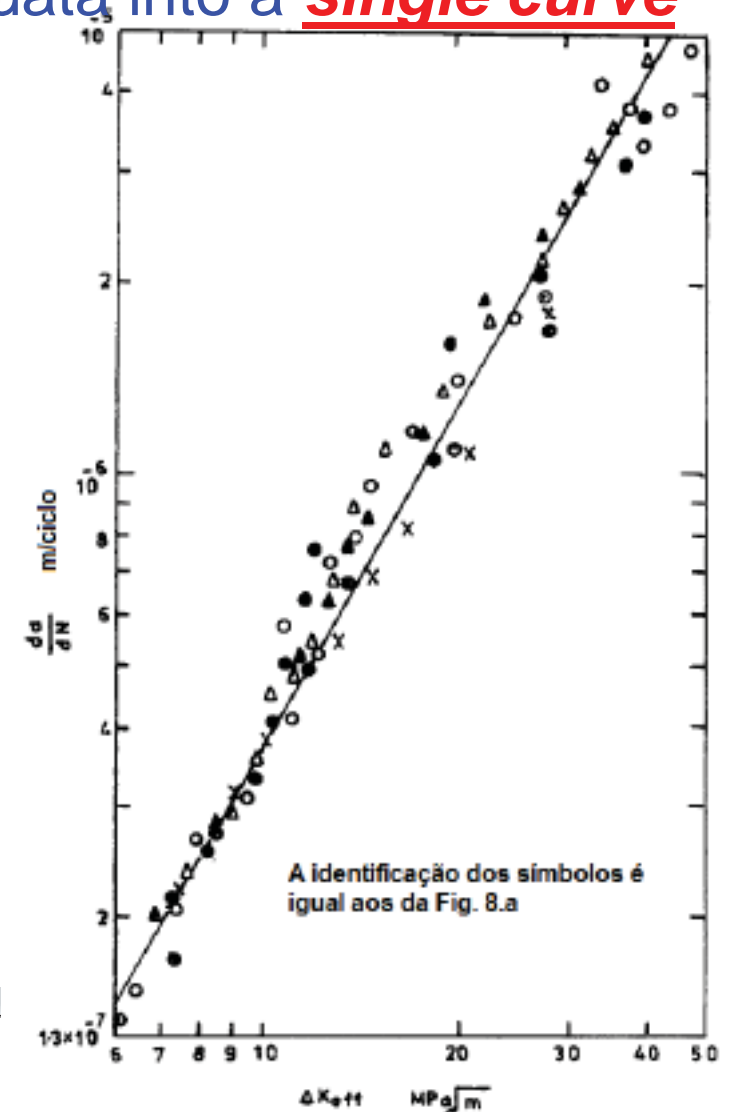
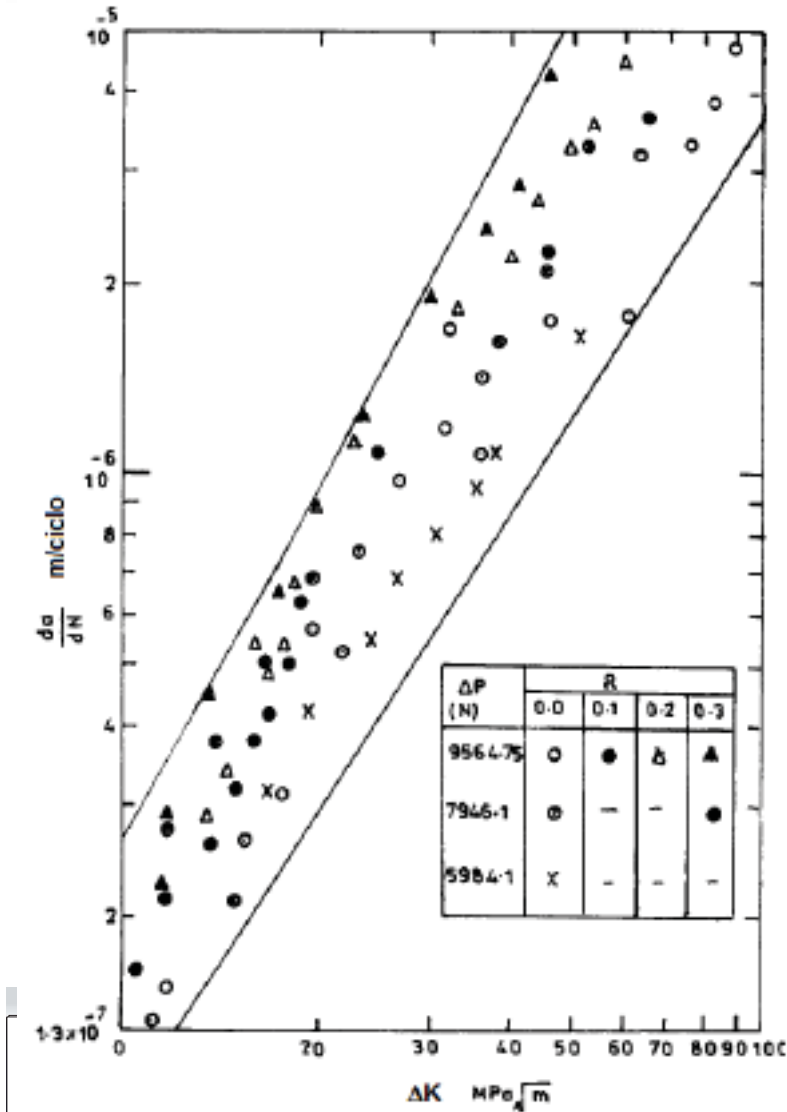


# Fechamento de Trinca por Plasticidade

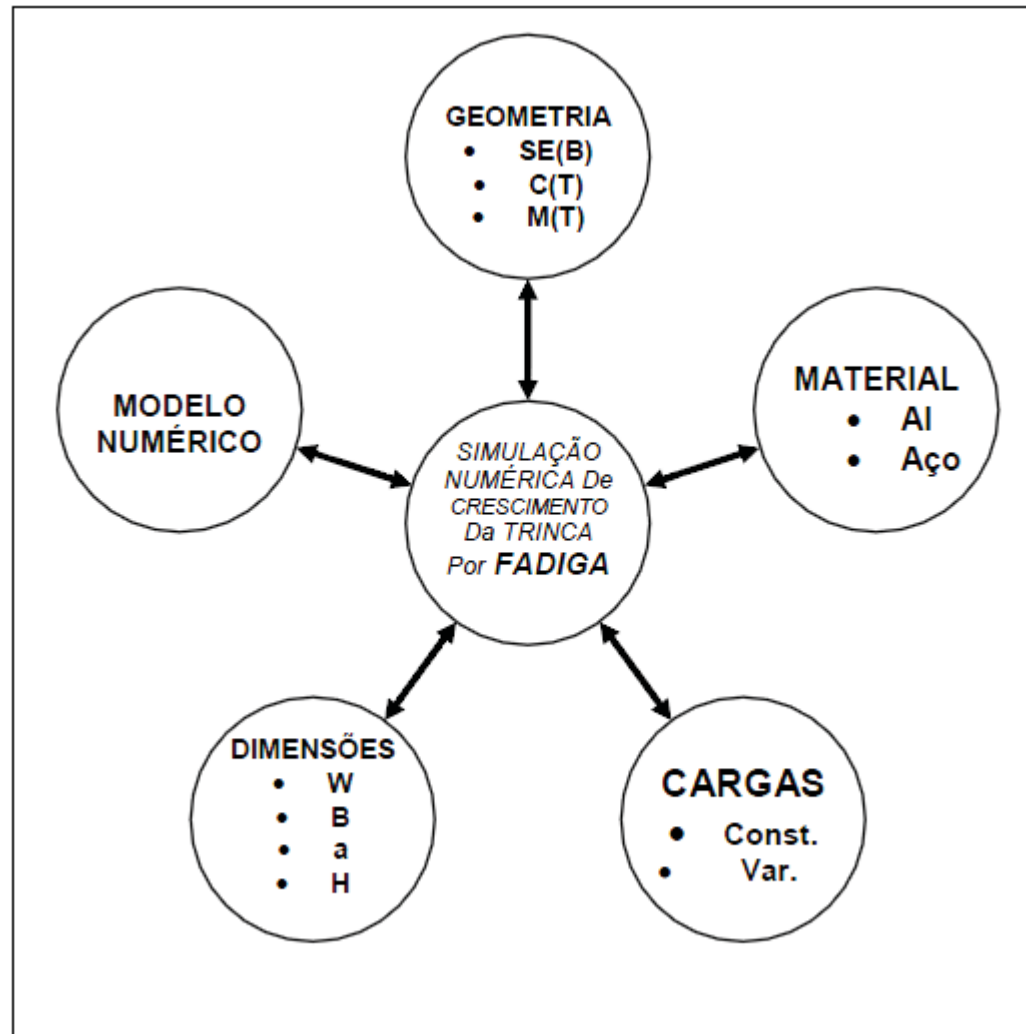


# Crack Closure

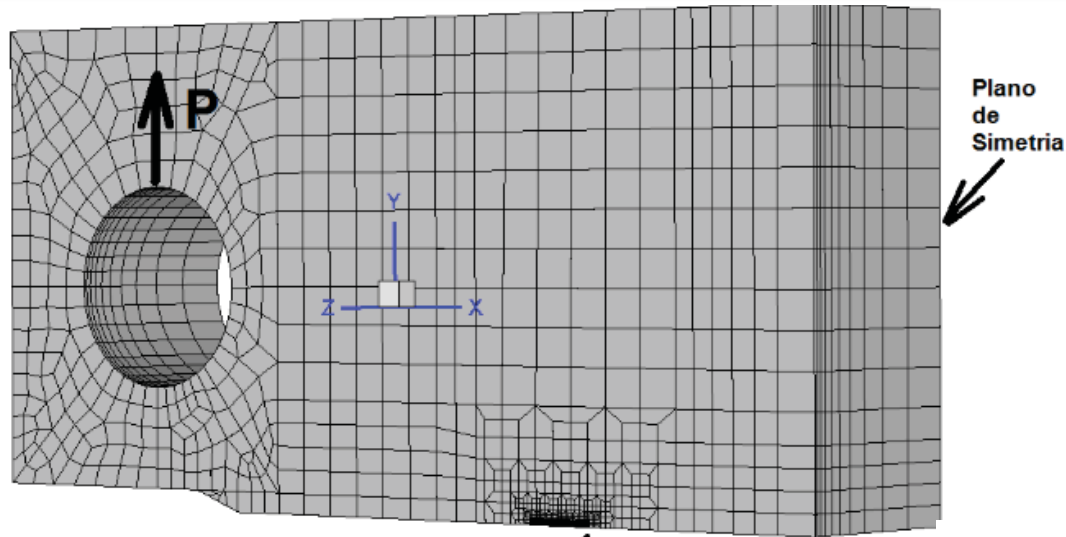
Consolidate data into a single curve



# Modelagem Computacional do Crescimento de Trinca por Fadiga



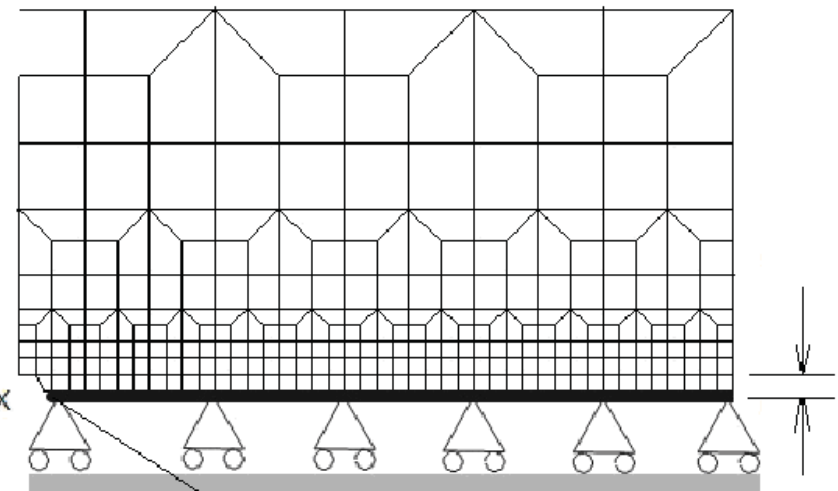
# Modelagem Computacional do Crescimento de Trinca por Fadiga



10 Camadas na espessura

Plano da Trinca

$(B/2) \times 2$

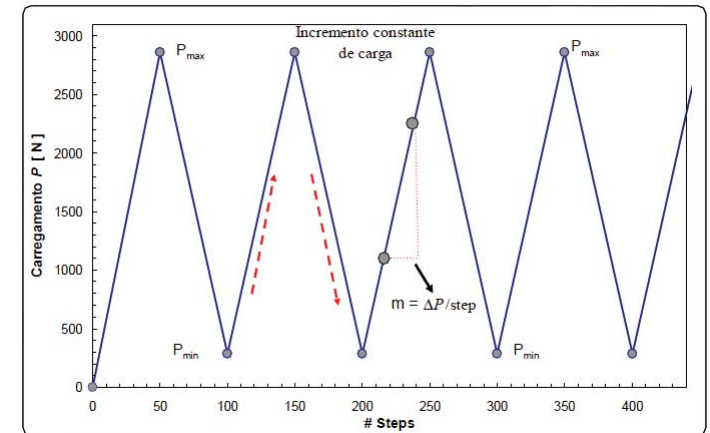
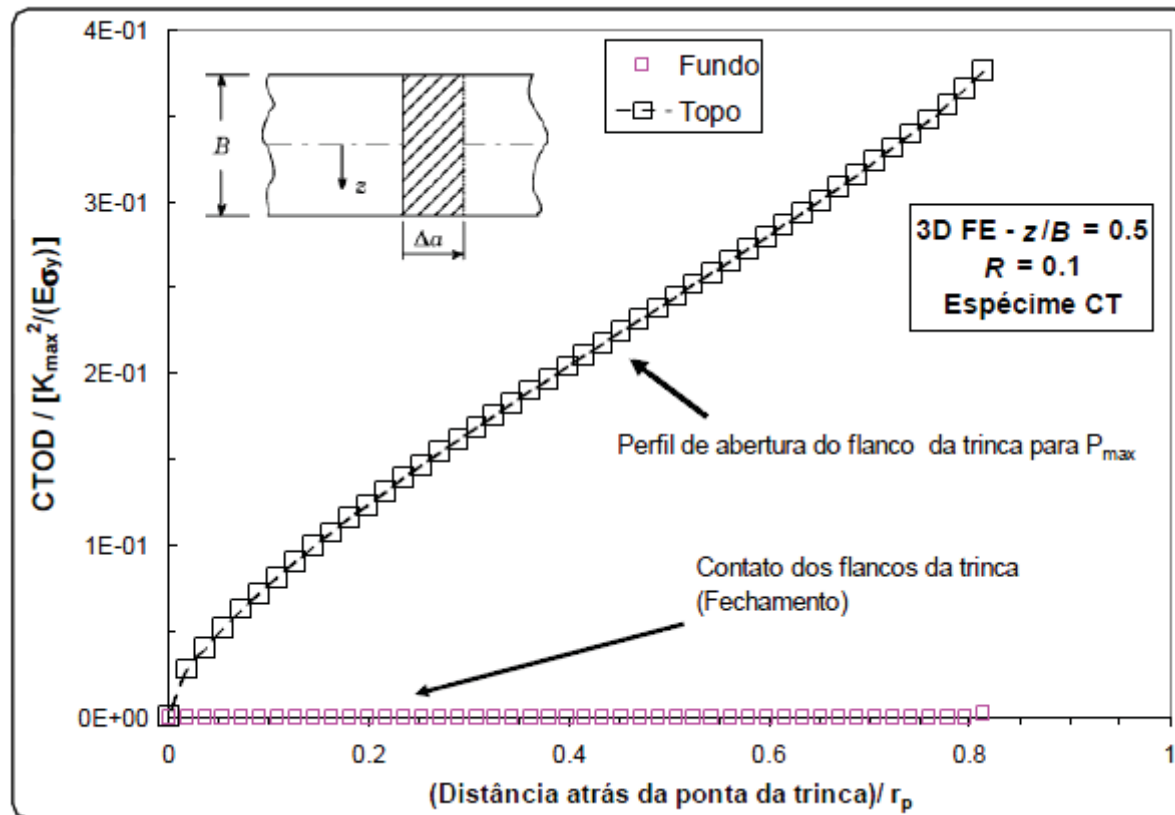


Ponta da Trinca



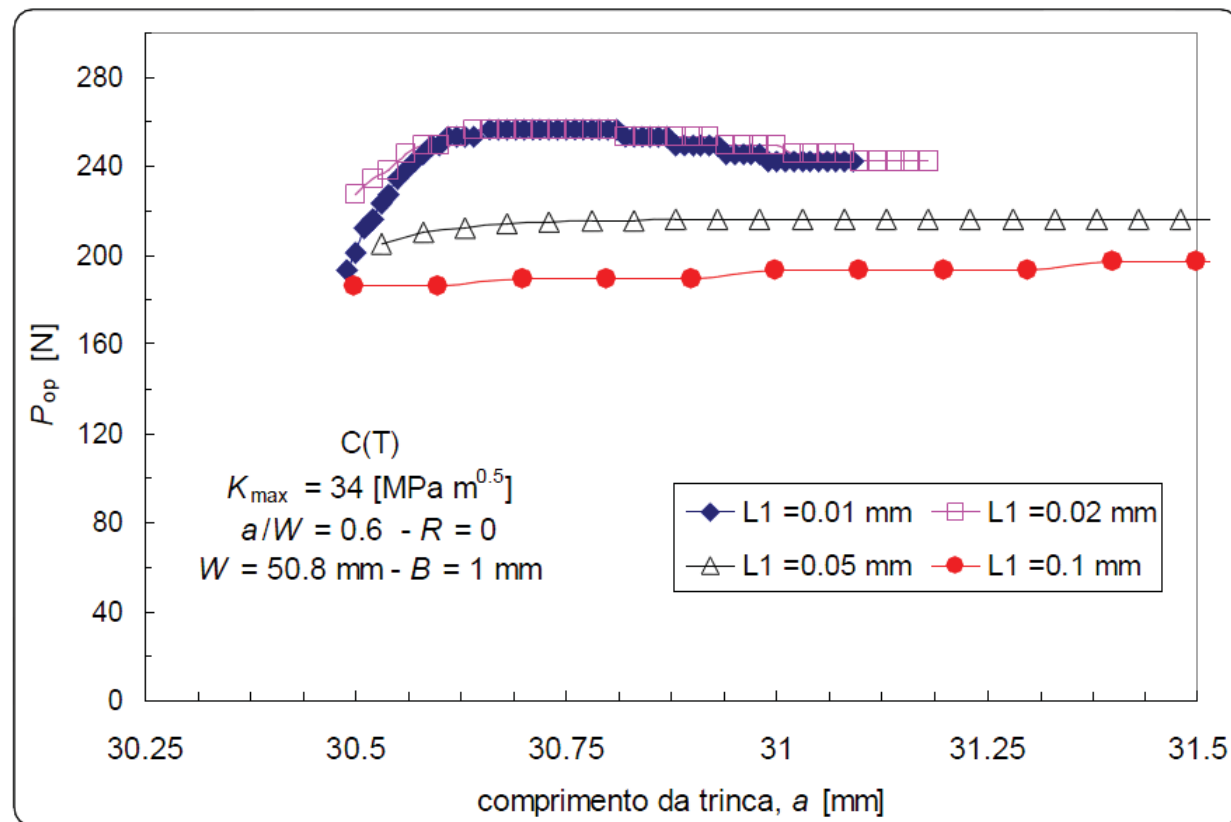
# Fatigue Crack Growth Behavior

## Fechamento de Trinca



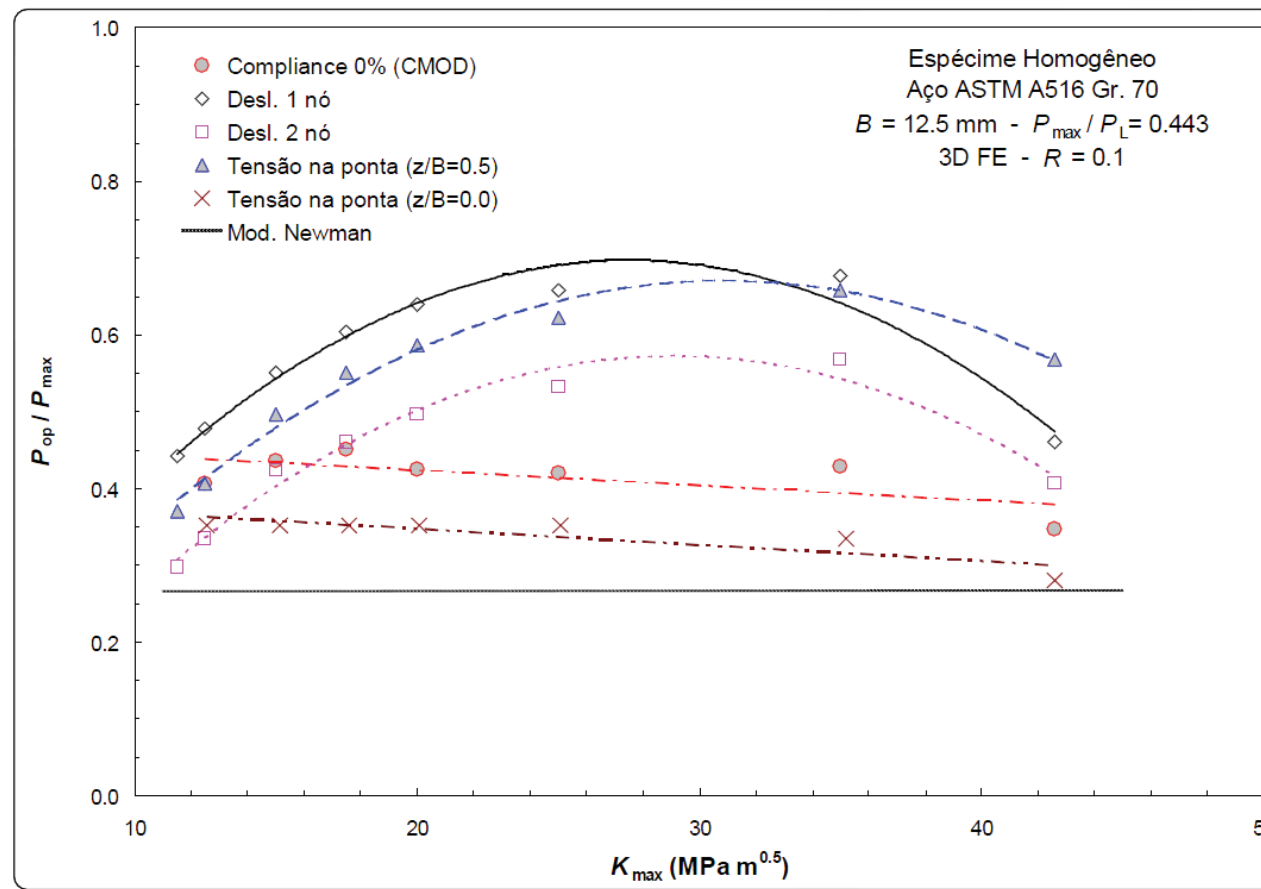
# Fechamento de Trinca

## Valores numéricos da Carga de Abertura de Trinca



# Fechamento de Trinca

## Comparação da Carga de Abertura de Trinca



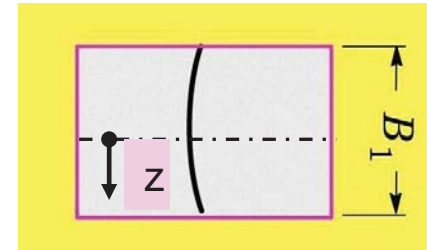
# Análise Numérica de Fadiga

## Força Motriz Efetiva

$$\Delta K_{eff} = f(P_{max}, P_o, a_j, t, W)$$

$$\frac{da}{dN} = C(\Delta K_{eff})^m$$

## Fechamento Parcial da trinca



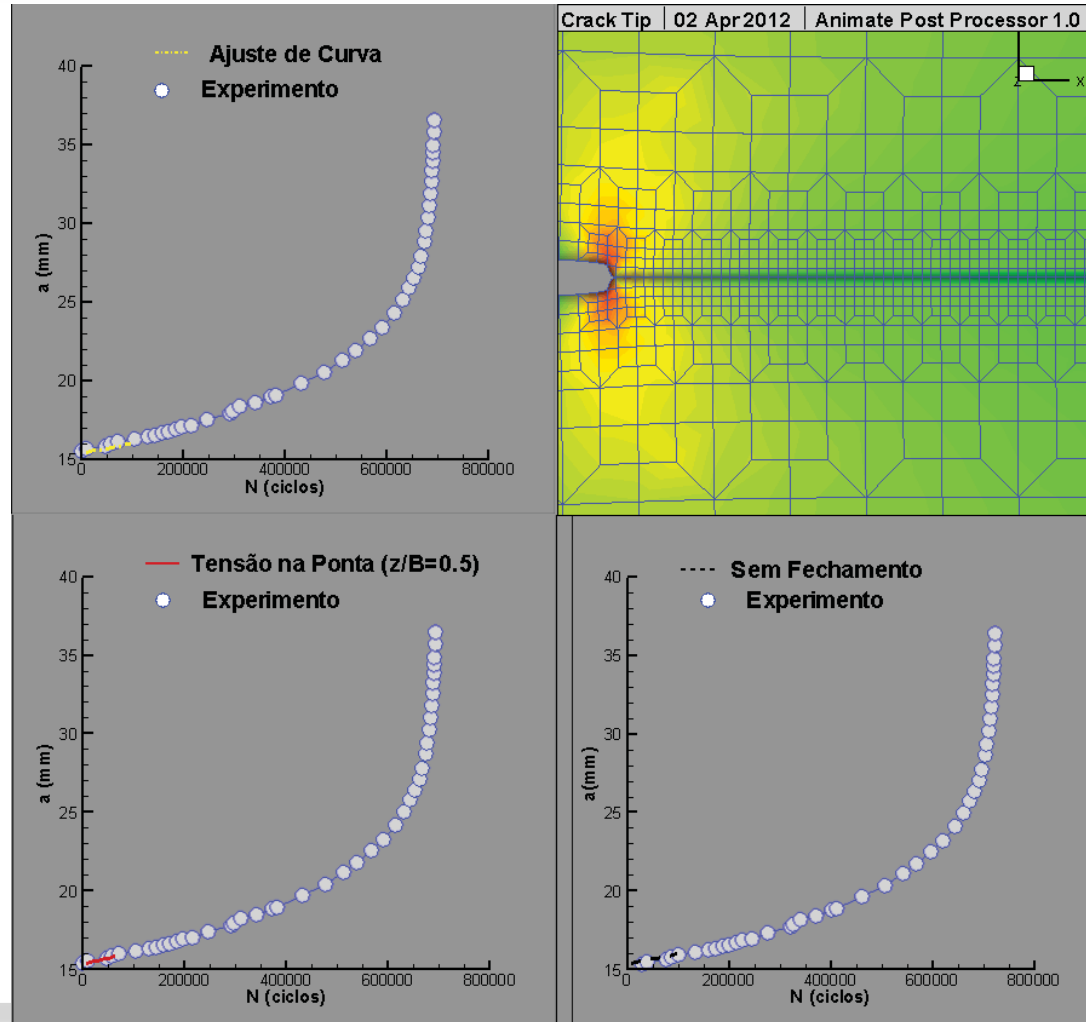
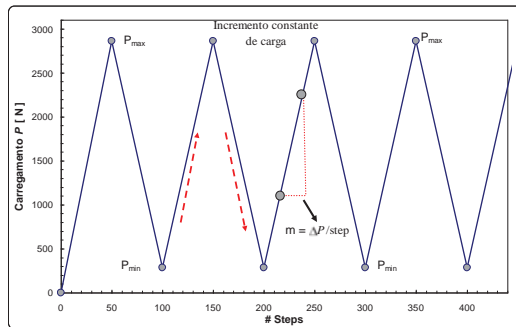


# Análise Numérica de Fadiga

## Propagação de defeitos

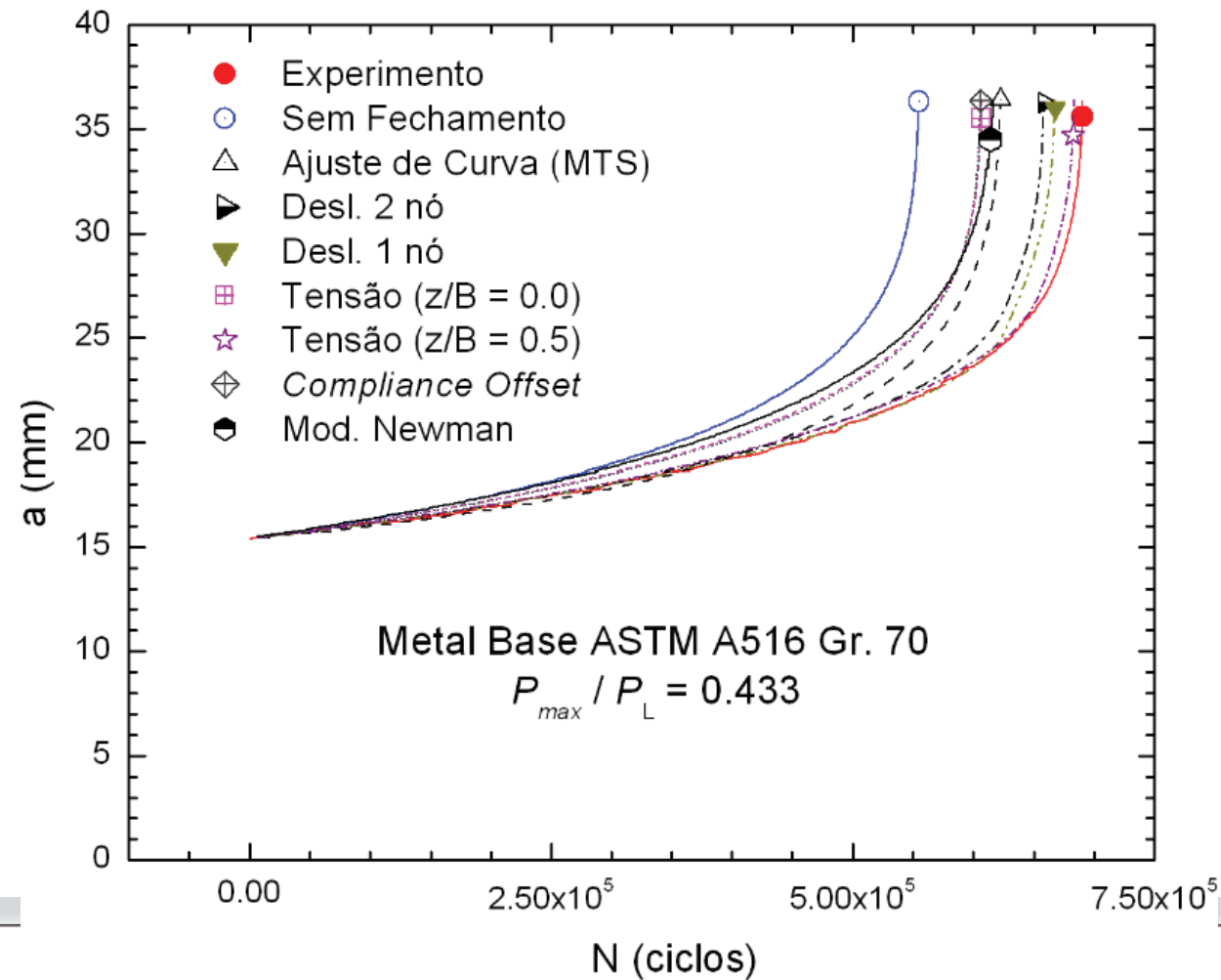
$$N = \int_{a_i}^{a_f} \frac{da}{C(\Delta K_{eff})^m}$$

$$\Delta K_{eff} = f(P_{max}, P_o, a_j, t, W)$$



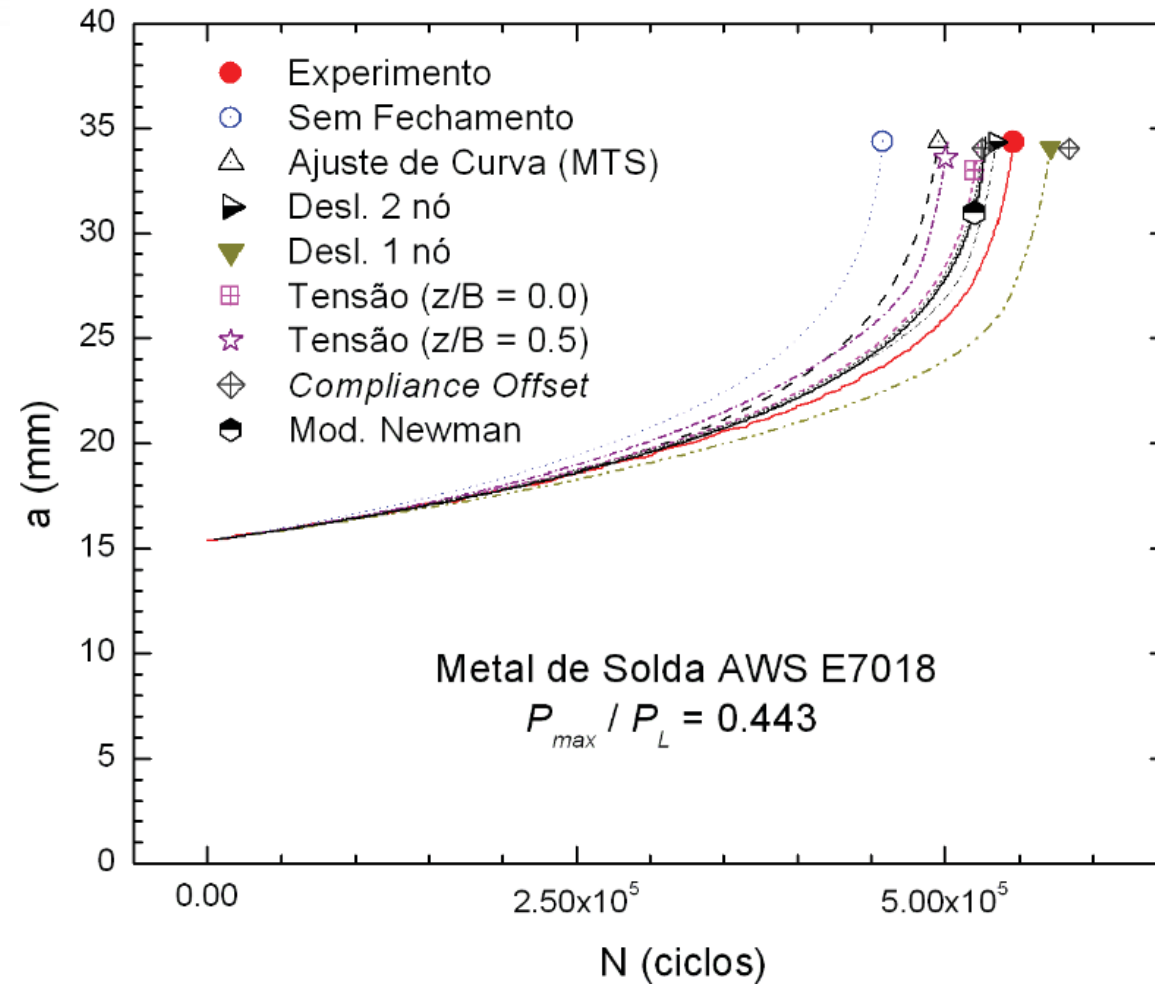
# Previsões da Vida à Fadiga

## Metal Base



# Previsões da Vida à Fadiga

## Metal Solda



# AGENDA

1. *Introdução (Introduction)*
2. *Conceitos da MFEL (LEFM Concepts)*
3. *Curvas de  $da/dN$  -  $\Delta K$  ( $da/dN$  Curves)*
4. *Efeitos da Razão de Carga (Effects of Load Ratio)*
5. *Tendências nas Curvas  $da/dN$ - $\Delta K$  (Trends in Fatigue Crack Growth)*
6. *Estimativas da Vida à Fadiga (Life Estimates)*
7. *Limitações da MFEL (Limitations of LEFM)*

# Plastic Zone Size

## Reversed Plastic Zone Size (Cyclic)

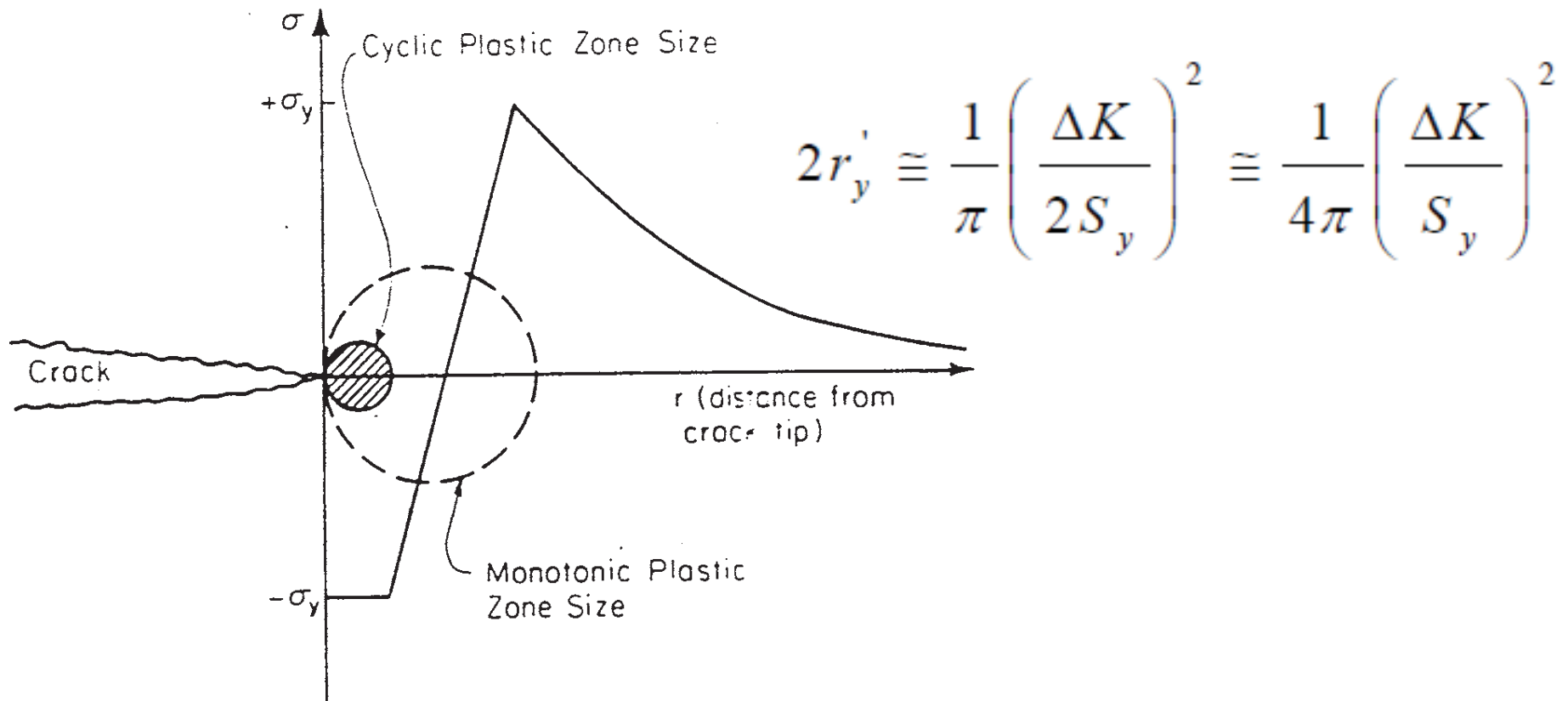
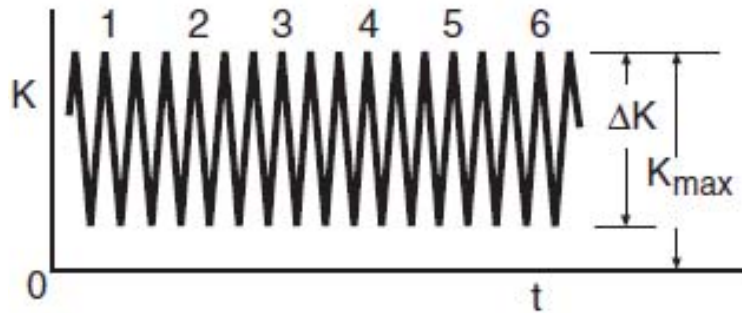


Figure 3.8 Reversed plastic zone size.

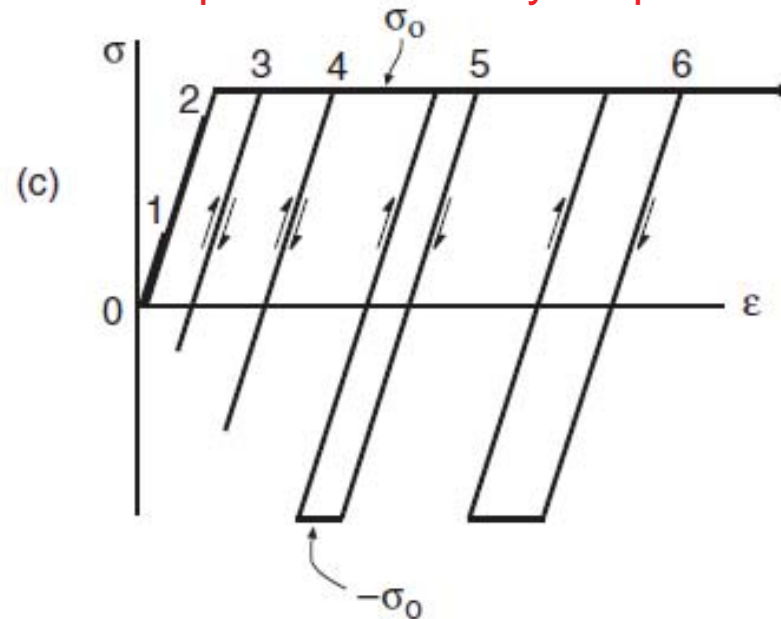
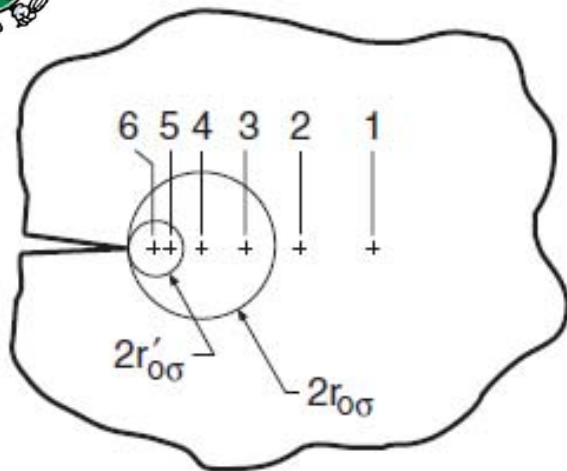
# Monotonic and Cyclic Plastic Zone



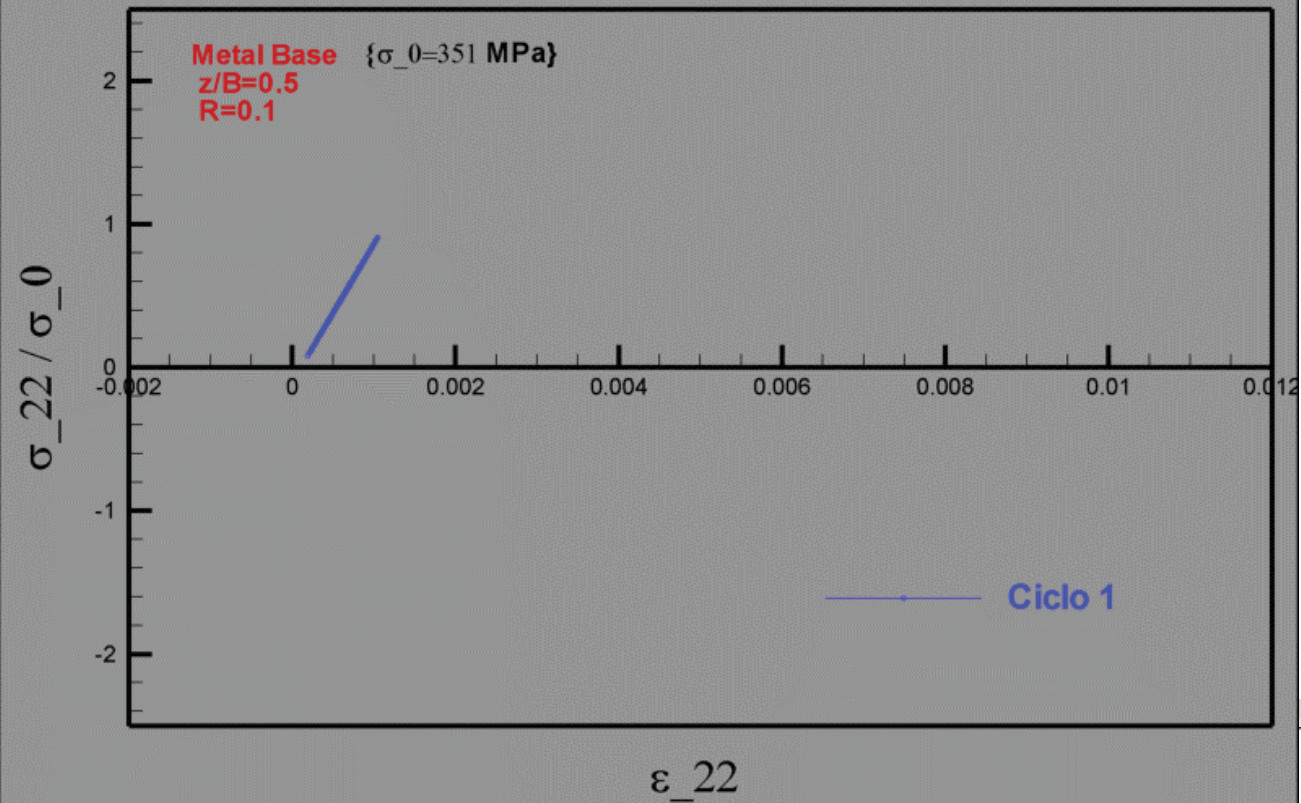
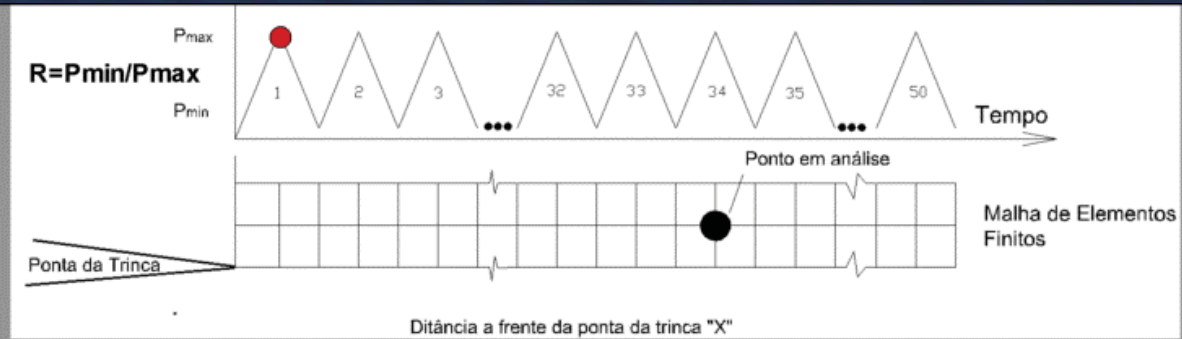
Ponto 1 Still outside plastic zone

Ponto 3 yielding begins with the point is inside monotonic plastic zone

Ponto 5 yielding in both compression and tension when the point is inside cyclic plastic zone



# Monotonic and Cyclic Plastic Zone



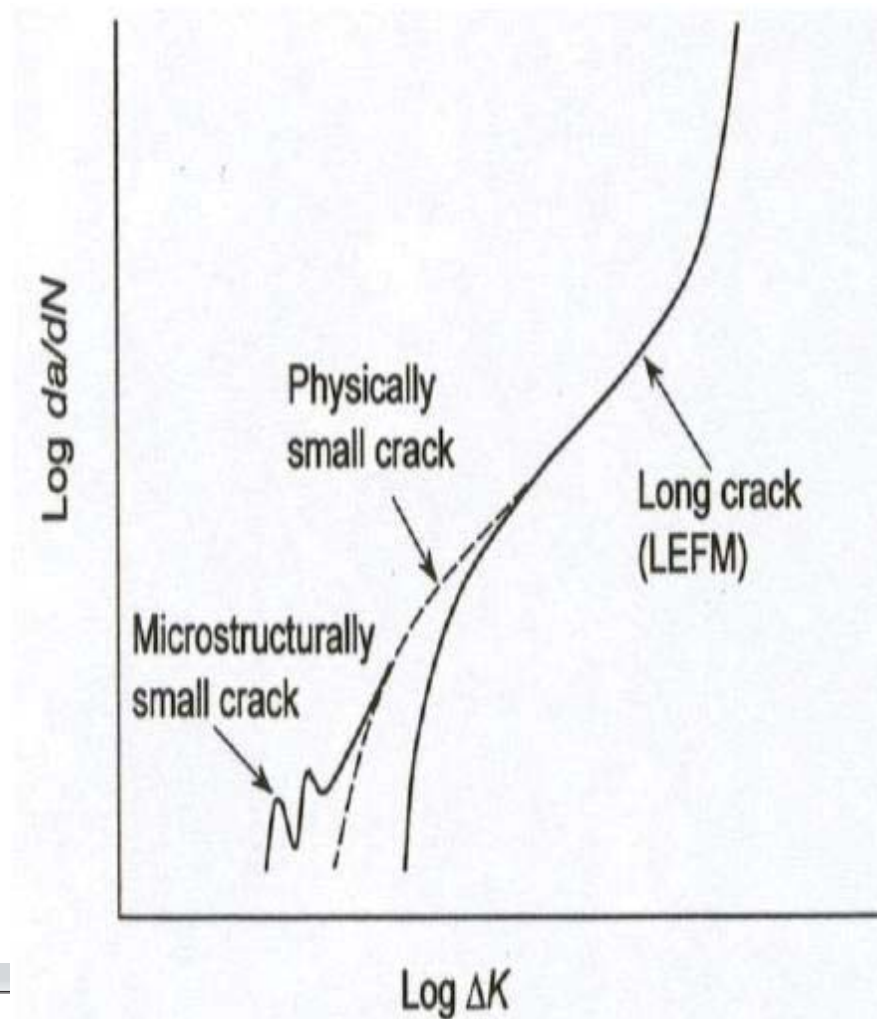
# Plastic Zone Size

## Reversed Plastic Zone Size (Cyclic)

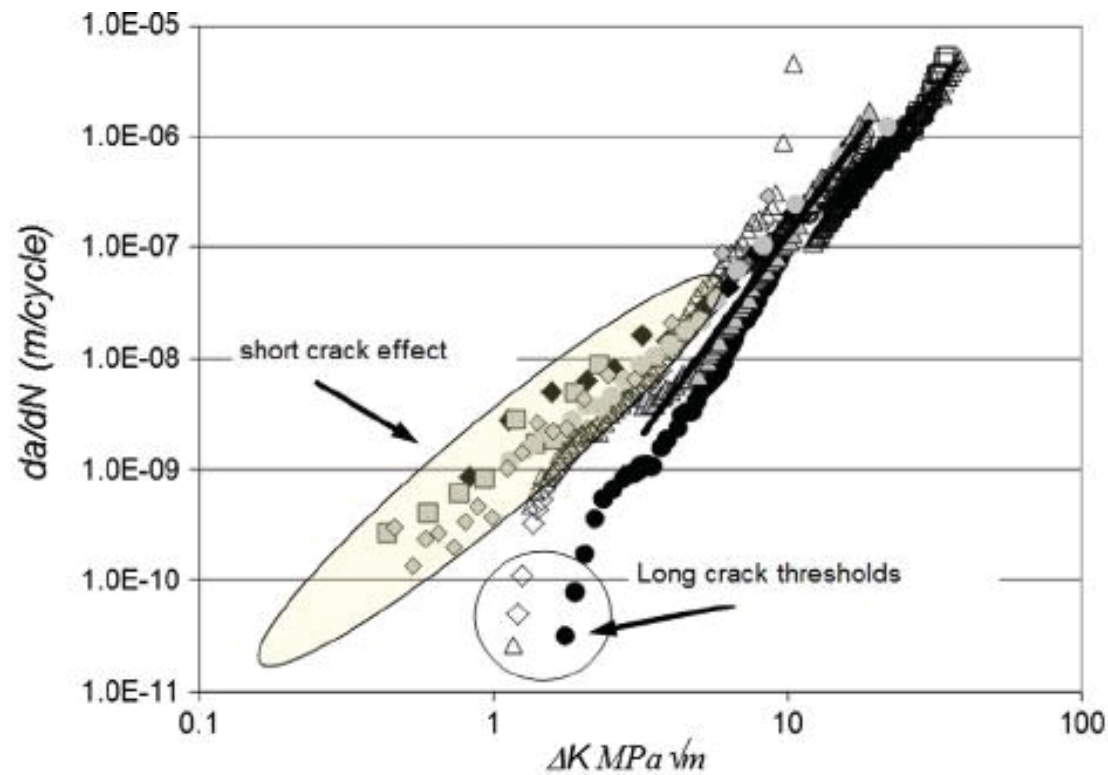
Because the cyclic plastic zone is usually much smaller than the monotonic plastic zone size, LEFM can often be applied to fatigue crack growth situations with good success even for materials that exhibit large plasticity.



# Short Crack Growth



# Short Crack Growth

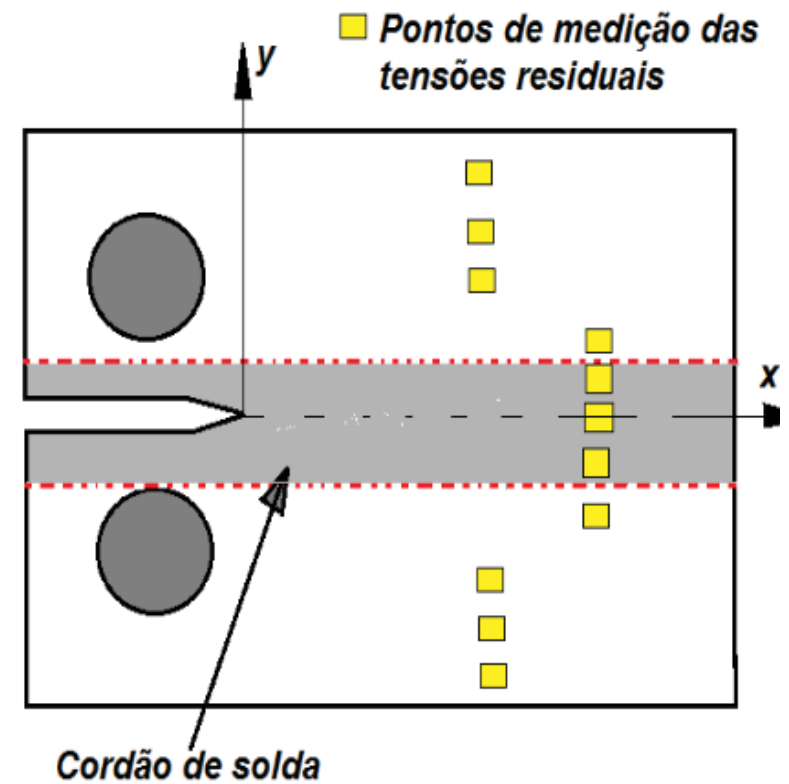


- |                              |                              |
|------------------------------|------------------------------|
| ◇ NASA Kmax                  | □ DSTO CT R = 0.1            |
| △ DSTO CT R = 0.1            | △ NASA R = 0.7               |
| ● NASA R = 0.1               | ○ DSTO CT R = 0.5            |
| ◆ Short crack Test 2 R = 0.1 | ■ Short crack Test 2 R = 0.7 |
| △ DSTO MT R = 0.2            | ● Short crack Test 3 R = 0.1 |
| ◇ Short crack Test 3 R = 0.7 |                              |

# Tensões Residuais



# Tensões Residuais



# Tensões Residuais

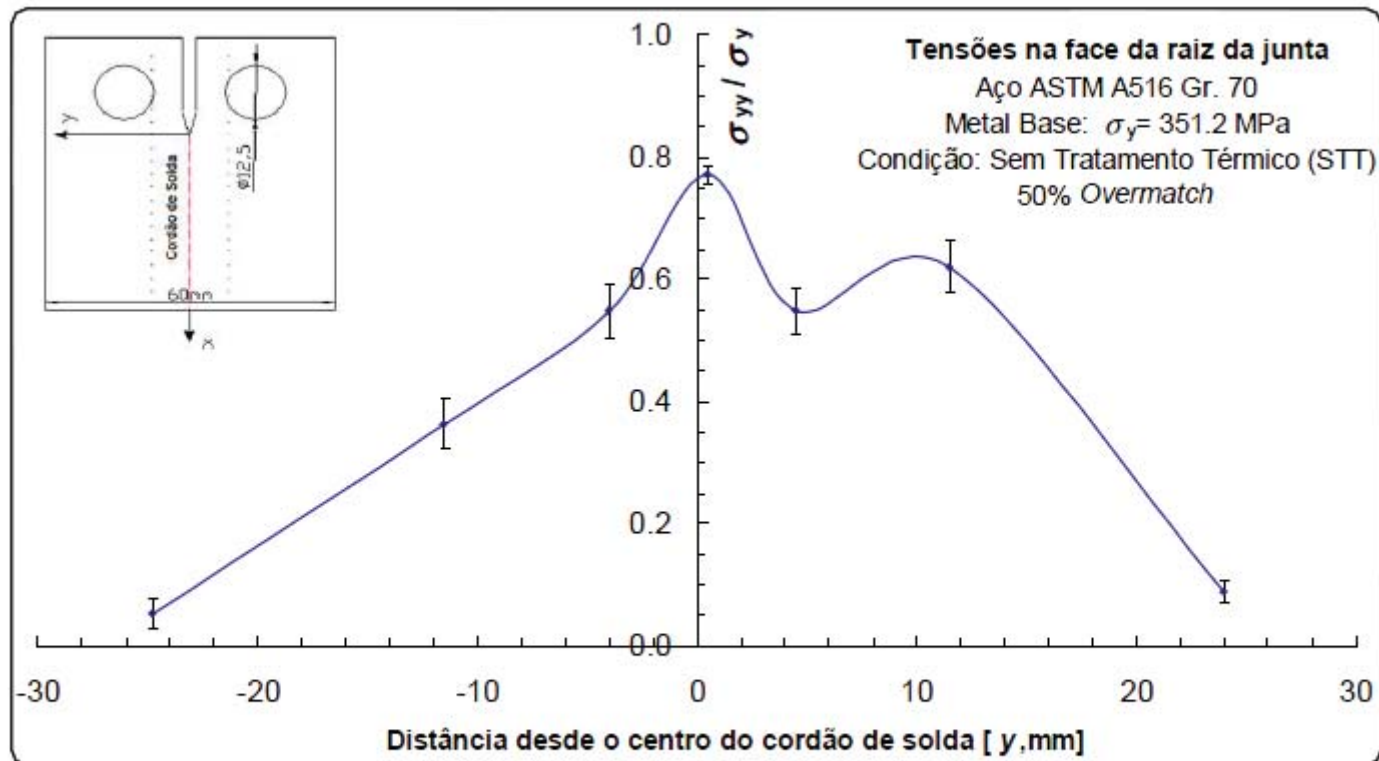


Figura 40: Distribuição das tensões residuais  $\sigma_{yy}$  na face da raiz do espécime soldado

# Tensões Residuais

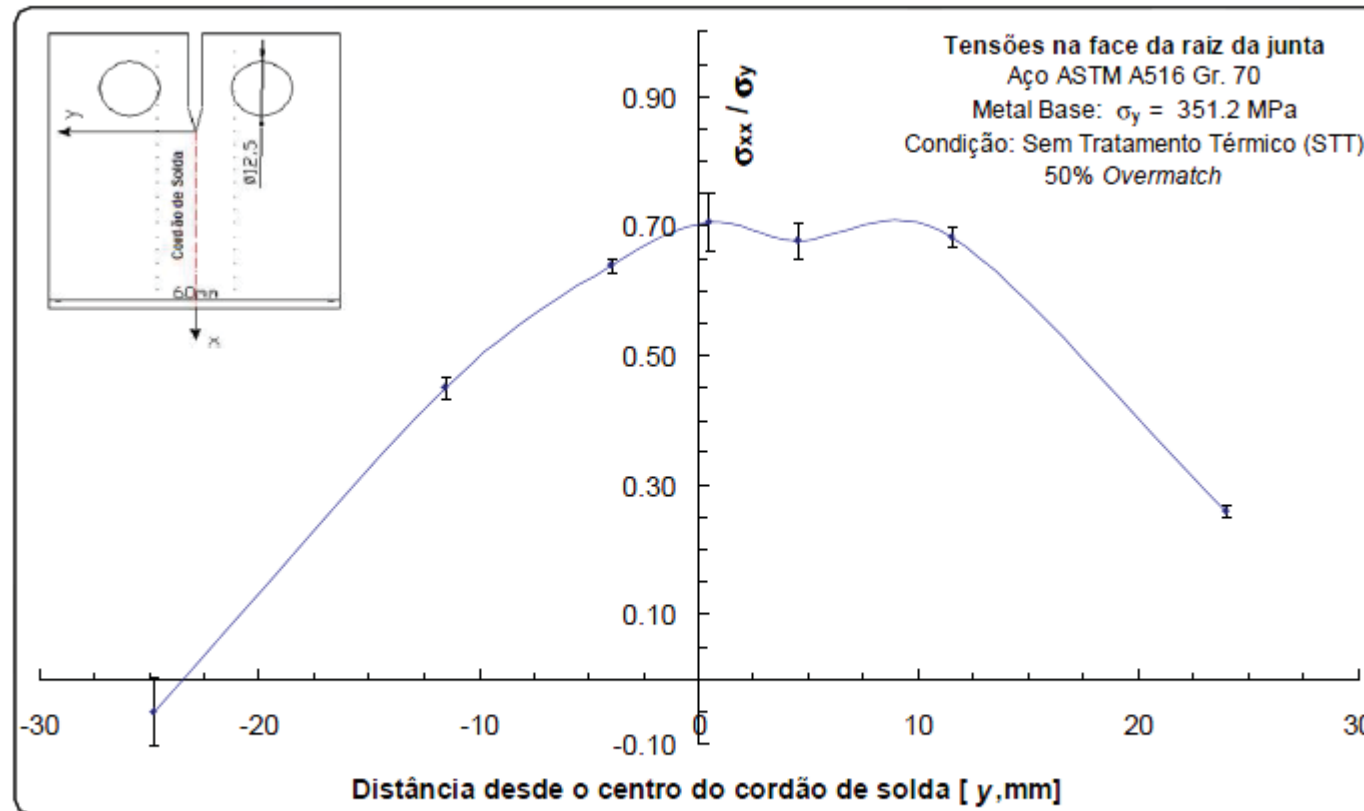


Figura 41: Distribuição das tensões residuais  $\sigma_{xx}$  na face da raiz do espécime soldado.

# Tensões Residuais

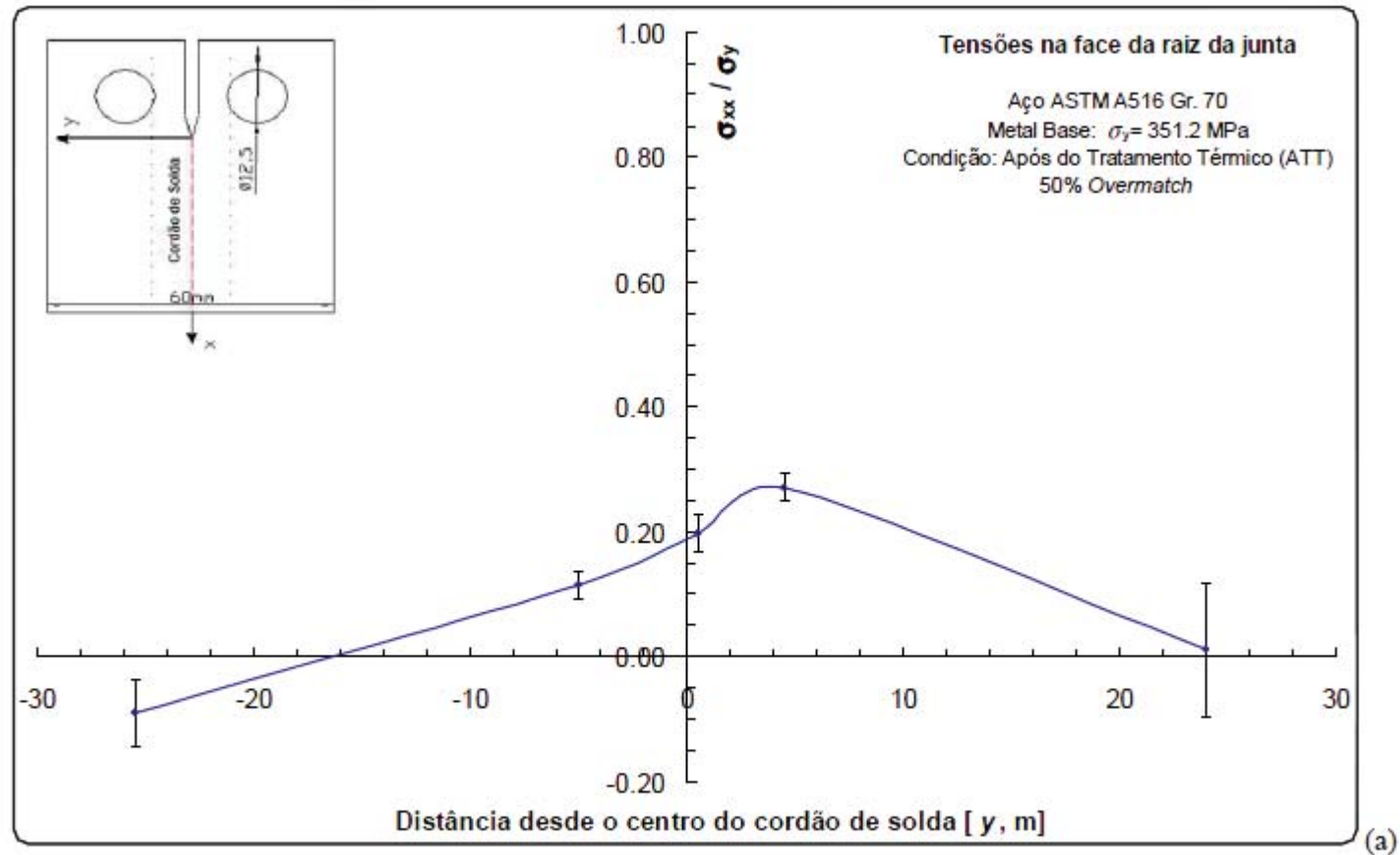


Figura 42: Distribuição da tensão residual  $\sigma_{xx}$  no corpo de prova soldado após os do tratamento térmico

# Tensões Residuais

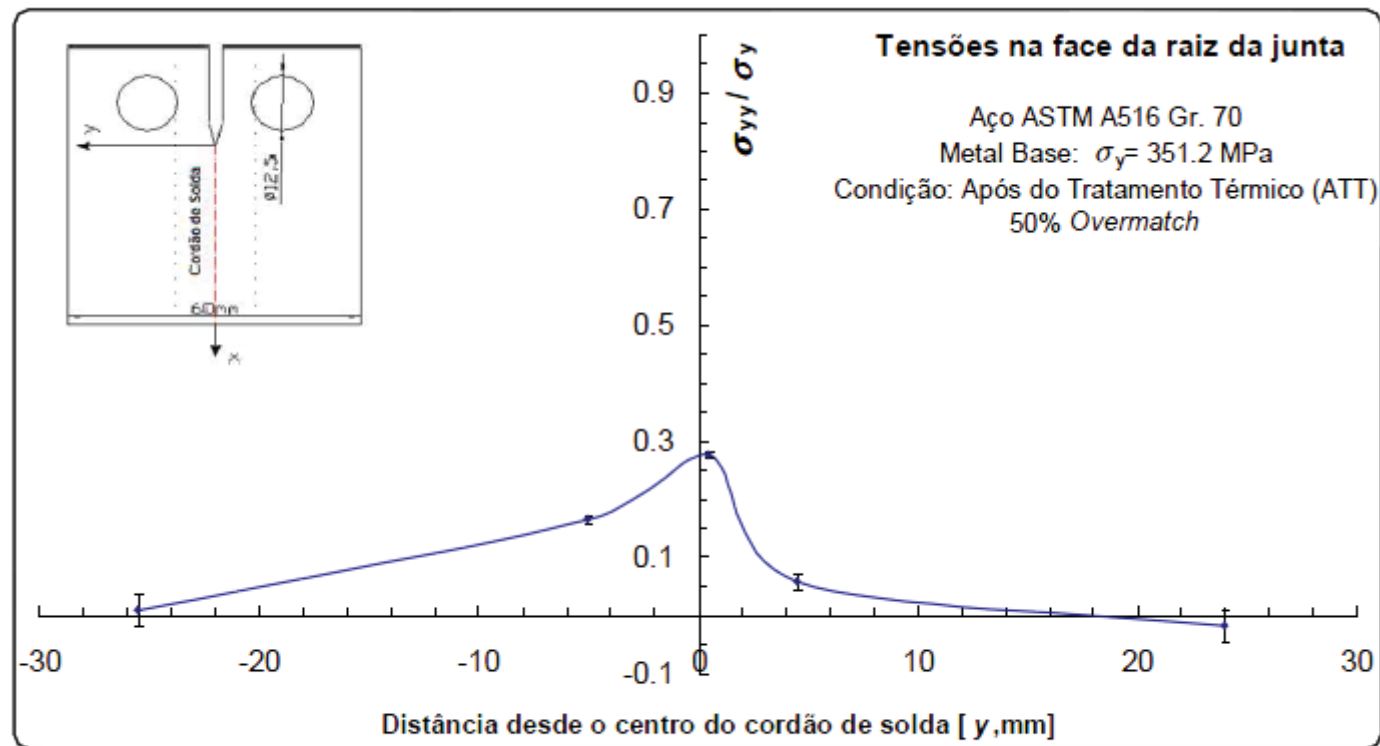


Figura 43: Distribuição da tensão residual  $\sigma_{yy}$  no corpo soldado depois do tratamento térmico





- OBRIGADO

